REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-12-2017

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Test Operations Procedure (TOP)
01-1-010A Vehicle Test Course Severity (Surface Roughness)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Yuma, AZ 85365-9498

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8. PERFORMING ORGANIZATION REPORT NUMBER
TOP 01-1-010A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Policy and Standardization Division (CSTE-TM)
U.S. Army Test and Evaluation Command
2202 Aberdeen Boulevard
Aberdeen Proving Ground, MD 21005-5001

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Same as item 8

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Defense Technical Information Center (DTIC), AD No.:

This TOP supersedes TOP 01-1-010 CN1, Vehicle Test Course Severity (Surface Roughness), dated 4 January 2012.

Marginal notations are not used in this revision to identify changes, with respect to the previous issue, due to the extent of the changes.

14. ABSTRACT
Provides a method of analyzing vehicle test course surface roughness. Describes use of profilometers and the conversion of profilometer data to power spectral density (wave number spectra) curves. Includes wave number spectra and other metrics of vehicle endurance test courses at ATEC Test Centers.

15. SUBJECT TERMS

Automotive test course	Roughness of roads	Wave number spectrum
Test course surface roughness	Profilometer	Vehicle test course

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	B. ABSTRACT	C. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	84	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 01-1-010A — 12 December 2017
DTIC AD No.

VEHICLE TEST COURSE SEVERITY (SURFACE ROUGHNESS)

* This TOP supersedes TOP 01-1-010 CN1, Vehicle Test Course Severity (Surface Roughness), dated 4 January 2012.

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1. SCOPE.

a. Vehicle test course severity is a product of many attributes used to define a test course. Among these attributes are surface roughness, grade, side slope, mud/dust, soil strength, radius of curvature, etc. This Test Operations Procedure (TOP) describes methods for determining vehicle test course surface roughness and grades by analysis of profilometer data as well as methods used for course maintenance. The calculated roughness metrics include normal displacement root mean square (RMS); wave number spectrum (WNS); international roughness index (IRI); and grade. This TOP includes the calculated metrics of vehicle endurance test courses at the U.S. Army Aberdeen Test Center (ATC), the Yuma Test Center (YTC), and the Tropic Regions Test Center (TRTC). These values are used in conjunction with the course descriptive information in TOP 01-1-011B[1**] and the vehicle group terrain type recommendations in TOP 02-2-506A[2] when developing a mission profile for endurance test planning.

b. Consistent course roughness is essential to properly analyze and compare reliability and durability data obtained years apart. Even when maintained, test course surface roughness will change depending on weather conditions and traffic density. Proper maintenance is needed in order to minimize the amount of variation that will occur.

2. FACILITIES.

Specific descriptions of the U.S. Army Test and Evaluation Command (ATEC) Test Center facilities are provided in Section 5, in the following paragraphs:

a. ATC courses, paragraph 5.1.

b. YTC courses, paragraph 5.2.

c. TRTC courses, paragraph 5.3.

3. MONITORING TEST COURSE SURFACE ROUGHNESS.

Test course roughness is monitored using several techniques that have been developed to track course roughness and minimize the variability of that roughness over time and to trigger timely and appropriate maintenance actions.

a. Hazardous course conditions are reported immediately by test vehicle operators or course inspection personnel upon detection. Hazardous conditions can include large potholes, standing water, snow and ice, wash-outs, or large rocks. Depending on the severity of the hazard, the course may be closed until repairs are made. Hazardous conditions are generally addressed within 24 hours.

** Superscript numbers correspond to Appendix F, References.

b. Courses are inspected at least monthly (except for those not regularly used). The courses are reviewed for hazards and excessive wear. At ATC, this also includes the use of a High-Mobility Multipurpose Wheeled Vehicle (HMMWV) operated at a pre-established speed for each course; the vehicle is instrumented to record suspension displacement and acceleration, which is compared to established roughness bands (see Appendix C). YTC also has an instrumented HMMWV, though it is no longer used regularly for course roughness assessment except if the YTC Profiler is disabled.

c. Courses are profiled periodically at ATC and YTC (see Appendices A, B, and D for a description of test center profilometers and processing techniques). Most courses are profiled monthly, with the exception of some of the longer courses at YTC which are profiled quarterly. (Note that profiling intervals are objectives that are dependent on equipment functionality, scheduling conflicts and weather permissibility.) The profiles are then analyzed for roughness, including using the wave number spectrum technique. Increases in roughness may signify the need to change course maintenance patterns. For example, secondary gravel roads at YTC go through a cycle of washboard build-up then grading. The washboard is graded when the wave number spectrum shows the amplitude at the washboard wave number (0.3 to 0.5 cycles per foot) to be approaching 5.0×10^{-3} ft^2/(cycles/foot).

4. TEST COURSE SEVERITY AND GRADE FROM THE SURFACE PROFILE.

a. The surface profiles of the test center endurance courses are measured on a periodic basis using profilometers. Off road profiling equipment is not very common, with each system being rather complicated and having characteristics which influence the final results. For decades ATC used a cart based profiler, as described in Appendix D. This system has been replaced by the rear mounted laser profiler system described in Appendix A. YTC uses a front mounted laser profiler system described in Appendix B.

b. The profilometer field measurements are processed to generate test course profiles, which present the test course elevations as a function of distance traveled along the course. Data are presented at discrete increments along the length, with a sample every 7.6 centimeters (cm) (3 inches (in.)) being very typical. These uniformly sampled spatial histories are analogous to signals in the time history domain. Many of the standard analysis techniques that are applied in the time domain are applicable in the spatial domain. Test course profile data are used to inform course maintenance decisions, are provided to modelers, are used to characterize the test courses for endurance test planning, and are retained for historical comparative purposes.

4.1 Test Course Root Mean Square (RMS).

a. The normal displacement RMS is a frequently referenced metric used to characterize terrain for military systems. The RMS is used in the North Atlantic Treaty Organization (NATO) Reference Mobility Model, ride quality specifications, many Operational Mode Summary/Mission Profile (OMS/MP) reports, and endurance test planning. Because an RMS value can be determined through a variety of processing routines, it is important to describe how RMS is calculated in this document. RMS values should not necessarily be compared if they are calculated from different methods.

b. Essentially the RMS is derived by first calculating the test course WNS. (WNS plots are presented throughout Section 5 of this document.) The WNS is the spatial domain analog to a Power Spectra Density (PSD) from the time/frequency domain. The WNS is typically calculated using Welch's method (with standard parameters of 256 feet (ft) blocksize, with 50% overlap, using a Hann window.) The x-axis of the WNS, or wave number, which has units of cycles per foot (or meter), is the inverse of the test course wavelength and is analogous to frequency in the time domain. The Y-axis of the wave number spectrum has units of vertical displacement squared divided by the analysis bandwidth (cycles per foot or cycles per meter). This is usually expressed as ft^2/cycle/ft. The test course RMS roughness is the square root of the area under the wave number spectrum between two wave numbers used as integration limits. The RMS value is, therefore, dependent upon both the WNS spectral shape and the integration limits.

c. While the definition of the integration bandwidths can be application specific, it has been generally accepted for military endurance testing that the RMS determination will be made between wavelengths of approximately to 0.15 to 20 meters (m) (0.5 to 64 ft). These integration bounds are partly arbitrary but are intended to cover the wavelengths which could influence a vehicle suspension at speeds typically used for endurance tests.

d. The ground excitation frequency can be estimated by multiplying the WNS wavenumber by the test item speed. It may be appropriate to use a longer wavelength integration bound if a test item is expected to traverse a course at a higher speed. Shorter wavelength content will excite subsystems with higher frequency inputs; longer wavelength content will excite subsystems with lower frequency inputs.

e. It should be noted that the course RMS process has switched post-processing filters recently in order to improve the capture of long-wavelength (near 64-ft) energy in the WNS. This change has resulted in an increase in reported RMS values for many courses since the implementation of the filter (circa 2015). Some of the reported RMS values have increased on the order of 10-50% due to this effect.

4.2 Other Surface Profile Statistics.

a. While RMS is a useful metric, in that it correlates to surface roughness and is well-established within the Army, it is not adequate to fully describe a test course as it relates to the surface profile's effects on the test item. There are many reasons for this.

(1) As described above, the RMS value is dependent upon the WNS curve shape, but the WNS curve shape is not dependent upon the RMS value. This means that two different courses with significantly different WNS content can generate the same RMS values.

(2) The RMS calculations overemphasize the contributions of long-wavelength content (up to 64 feet) and underemphasize the shorter wavelengths. The content in the shorter wavelengths may have a greater influence on specific subsystems, as discussed in the section on IRI.

(3) The RMS calculation process “averages out” transient features; this means transient course content such as bumps and potholes, which can have a serious influence on a test item, will have little influence on an RMS value.

(4) Course grades, side slopes, and curvature create effects distinct from course roughness, and are therefore not described by RMS. Whereas roughness has an effect on suspension and fatigue characteristics, grades will have an influence on powertrains and braking. Similarly side slopes and curvature primarily (and often interdependently) affect steering, side loading, and lateral stability.

(5) RMS does not convey how a test item would respond to a course at a given speed. This is an impossible task for any single profile based metric given the variety of test items which will respond in different ways to the same inputs.

b. For the reasons listed above more metrics than a simple RMS value should be conveyed when describing a test course.

4.3 International Roughness Index (IRI).

a. As mentioned, RMS is a useful metric in that it correlates to course roughness and its use is well-established within the Army. In addition to RMS, there are well-established methods in the civilian world that approach the concept of course roughness using different analytic methods, one of which is the IRI.

b. The IRI was developed in the 1980’s to provide a common standard of roughness analysis for roads and highways throughout the world, and has been in wide use throughout the world since that time. The IRI algorithm (as described in World Bank Technical Paper Number 45[3]) processes longitudinal-elevation road profiles by essentially simulating the response of a heavily damped quarter-car model traveling on the road at a fixed speed. The standard simulation speed is 80 kilometers per hour (km/h) (49.7 miles per hour (mph)). The IRI algorithm produces a filtered response of the suspension displacement (or rate) between the quarter-car sprung and unsprung masses, as well as the “Average IRI” (AVEIRI) metric. The AVEIRI characterizes how much the simulated suspension displaces over a given distance. Specifically it is the average of the absolute value of the filter response. A road which is “rougher” will result in more suspension displacement per mile. AVEIRI values for military off-road endurance courses can be much higher than those typically analyzed in civilian studies that generally concentrate on primary road surfaces.

c. Compared with RMS, the IRI is superior at characterizing how much the terrain would cause a plausible vehicle suspension response. The IRI acts as a frequency domain transfer function, filtering out the long wavelength content which very often drives RMS values. One of the weakness of the IRI comes from its development in the civilian world, where civilian roads, vehicles, and speeds may differ significantly from those in the military. Furthermore the AVEIRI broadly characterizes suspension displacement response, which is certainly an important focus when maintaining civilian roads and highways, but ignores other ways a vehicle may respond.

d. IRI should be viewed side-by-side with RMS as a metric that characterizes roughness, but with more focus on the shorter wavelengths of a course. An additional benefit of IRI is that it is an established metric, which enables a comparison of test center courses with other roads which have been measured with the IRI. Finally, AVEIRI can be useful to differentiate two courses that may have comparable RMS values but different AVEIRI values.

e. The varied terrains traversed by military vehicles relative to civilian vehicles results in a high variance in speeds. IRI, being a velocity-dependent parameter, is therefore presented at three speeds in this report: the standard IRI speed of 80 km/hr (49.7 mph), which is most appropriate for high-speed primary and secondary roads; a speed of 40 km/hr (24.9 mph), more appropriate for rougher secondary and trails terrain; and a speed of 25 km/hr (15.5 mph), which would be generally appropriate for cross-country terrain. Using the terminology presented in World Bank Technical Paper Number 45, the different IRI parameters would be designated Reference Average Rectified Slope (RARS) 80, RARS 40, and RARS 25.

4.4 Longitudinal Grades.

The longitudinal grades along the course length can be calculated and statistically characterized. Longitudinal grade is an important metric in that many vehicle specifications indicate a maximum grade that can be traversed. The longitudinal grade profiles are useful for assessing powertrain, longitudinal chassis loading, and braking. Grade is simply the change in height over a given distance change (“rise over run”). For the analysis in this document, a distance change of 64 ft was used. A distance of 64 ft was considered an appropriate length for typical off-road speeds wherein a significant change in momentum might occur, thus requiring accelerator or brake input to maintain speed. The longitudinal grade values of a profile were calculated along the length of the course by simply taking the difference in elevation between the sample point 32 feet before and 32 feet after each location.

4.5 Statistical Assessments of Elevation Profiles and Terrain Severity Parameters.

Superior characterization of the terrain can be achieved with a more in-depth statistical analysis of elevation profiles. This may include calculating statistics of the elevation profiles themselves, or presenting statistics on test course characteristics as they change along the length of the course.

a. Calculating the standard deviation, skewness, kurtosis, and percentile ranges is a simple procedure. Generally the elevation profile is high pass filtered prior to statistical analysis. The skewness and kurtosis values are scaled by the standard deviation value. A test course with a purely Gaussian profile will have a skewness value of 0 and a kurtosis value of 3. The skewness of an elevation profile indicates the degree to which the elevation profile deviates more positively or negatively from the mean. For example, Perryman No. 3 Course (at ATC) has a skewness of approximately 1.15 while Perryman No. 2 Course has a skewness of approximately 0.09. The kurtosis value characterizes the extremal deviations from the mean, relative to the standard deviation. For example, Perryman A Course and Perryman No. 1 Course are comparable in many respects, however their kurtosis values differ (respectively 5.39 and 12.39). This is indicative of the nature of their deviations (Perryman No. 1 Course has sharper potholes.)

b. The test course surface profile parameters introduced (RMS, IRI, Grades), can be better understood when keeping in mind their variations along the course length. This is most notably the case in the longer YTC endurance courses. Several statistics help provide a better overall picture of each course. For example, maximum RMS and maximum Grades may help determine the limitations of a course as it relates to the vehicle's specification, but the means of these parameters may provide a better indication of the average effect on the vehicles. For each YTC test course, the following statistics were calculated for each roughness parameter based on 1024-ft section lengths: minimum, mean, and maximum. For grades, the following statistics were calculated: root-mean-square average (standard deviation) and maximum absolute value.

5. WAVE NUMBER SPECTRUM ANALYSIS OF GROUND VEHICLE TEST COURSES.

The various endurance test courses at ATC and YTC are regularly measured for their surface roughness using profilometer systems. The courses measured and the resulting wave number spectra are described in this Section by each test center. These curves are plotted in terms of power per unit spatial frequency versus spatial frequency. Hence, the units will be ft^2/cycle per ft = ft^3 for the ordinate and cycles per ft = ft^{-1} for the abscissa. These spectra are general characterizations of the surface roughness of each test course and should be considered typical for that course. Activities that require actual surface roughness at the time of a test (e.g., model validation, ride quality) should conduct a terrain measurement at the time of the test. The wave number spectra for each course are presented in the following paragraphs. Sufficient data exists such that percentile spectra (10^{th} and 90^{th}) were computed in addition to the average spectrum (note that the average and percentile bands do not reflect any one profile event, but rather these statistics for each frequency bin). Based on the existing data sets and maintenance practices, the test course spectral content can reasonably be expected to be within those spectral bounds 80% of the time. Excursions above or below the percentile spectra should not be significant except on courses where significant washboarding is allowed to develop before grading. As can be expected, longer wavelength content is less sensitive to wear, weather, and maintenance. As such the shorter wavelength content shows a greater range between percentile spectra.

a. The ways in which the spectral content influences a vehicle depends on the speed at which the test item is traversing the test course. For example when traveling at 25 mph (36.67 feet per second (ft/sec)), terrain content at the 30 ft wavelength will excite a vehicle with a frequency of 1.2 Hertz (Hz), while content at the 3.67 ft wavelength will excite the vehicle with a frequency of 10 Hz. Changing the speed will proportionally change the frequency those wavelengths excite. If the item under test is understood well enough to know how frequency content influences its various subsystems, and the test course operation speeds are known, then insights can be gained as to how the test course spectral content will influence the test item. In general, low frequency content will affect universal joints, transmissions, and other drive train components. Higher frequency content will affect wheel bearings, shock absorbers, and other suspension and structural components. (The low- and high-frequency effects should also be evident when observing how the IRI relates to the RMS value.)

b. Terrain or test courses with noticeable periodicities will have WNS curves with distinct peaks or spikes, which are most noticeable when plotting the vertical axis on the linear scale. Periodicities with wavelengths less than 6-ft are generally considered washboarding, while periodicities at wavelengths greater than 6-ft are referred to as undulations (or similar terms). Extremely small periodicities (less than 1-foot wavelengths) are most often soft-soil track pad indentations and generally do not affect vehicle vibrations.

c. Generally the WNS content is broad spectrum in nature. Occasionally focus is paid to the general slope of the WNS, as presented in the log-log domain. Two courses may have the same slope but will have different RMS values if their curves are offset from each other. WNS curves generally slope downward from left to right, with the imperfect fits to averaged WNS curves having slope values typically ranging from -2.5 to -1. A slope of -2 would indicate the terrain has, on average, an amplitude-to-wavelength ratio that is a constant; steeper slopes (less than -2) indicate more emphasis on long-wavelength content; and shallower slopes indicating an emphasis on short-wavelength content. The downward slope makes sense when considering the WNS content at a wavelength is proportional to the profile height variance at that wavelength. A height change of 2 in. every 2-ft is significant, while a height change of 2 in. every 20-ft is less significant.

5.1 Aberdeen Test Center (ATC) Courses.

5.1.1 Summary.

a. The nature of the terrain at ATC, and its associated severity, is greatly influenced by the climate and local geography. Munson Test Area (MTA), Perryman Test Area (PTA), and The Automotive Engineering Test Facility (ATEF) are all situated in relatively low lying areas located near the Chesapeake Bay. Churchville Test Area (CTA) courses are located more inland, where naturally occurring hills enabled the creation of courses with extended grades. Natural creeks and streams run in close proximity to many of the PTA courses. Precipitation (rain, sleet, or snow) will accumulate and can remain on the ground for days after it falls. The degree of moisture content in the ground (from dusty to oversaturate) will influence the wear patterns that test operations will produce. Refer to TOP 01-1-011B Vehicle Test Facilities at Aberdeen Test Center and Yuma Test Center for more information.

b. A more detailed description of ATC courses is given in the following sections. Tables characterizing ATC course RMS, IRI, statistics, and Grade values are respectively presented in Tables 1 through 4. The RMS values presented in Table 1 are derived from the WNS curves, as discussed in paragraph 4.1. The Standard Deviation of RMS characterizes the degree to which the course measurements may vary over time. The elevation profiles which lead to Tables 1 and 3 were high pass filtered (forward and backward) through a 4th order high pass Butterworth filter with a cut off frequency of 1 cycle/128 ft. For some of the test courses, the higher speeds used in the IRI analysis are unrealistically high. These higher speed IRI values are still presented, though noted, in case they provide any informational value. The maximum Grade values presented in Table 4 indicate the single largest Grade a vehicle will climb (or descend) while traversing the course, while the Standard Deviation and 80% Range of the Grade values characterizes how much of the test course the test item spends “at grade”.

TABLE 1. SUMMARY OF ATC COURSE RMS VALUES

COURSE NAME	AVERAGE RMS, in.	STANDARD DEVIATION OF RMS, in.
3-Mile Straight-away	0.09	0.01
Belgian Block	0.69	0.03
Improved Gravel Road	0.25	0.07
Perryman A	0.41	0.07
Perryman No. 1	0.38	0.04
Perryman No. 2	0.81	0.08
Perryman No. 3	2.98	0.07
Perryman No. 5	2.96	0.07
Churchville C	0.22	0.04
Churchville B	1.61	0.08
ATEF Paved	0.05	0.01
ATEF Gravel	0.17	0.03
Churchville B Smooth	0.39	0.04
Churchville B Rough	2.55	0.15

TABLE 2. SUMMARY OF ATC COURSE IRI VALUES

COURSE NAME	AVERAGE IRI AT SPEED, in./mile		
	50 mph	25 mph	15 mph
3-Mile Straight-away	169	255	299
Belgian Block	1788	1961	2144
Improved Gravel Road	382	494	559
Perryman A	611	761	850
Perryman No. 1	579	702	770
Perryman No. 2	1118	1257	1350
Perryman No. 3	2521	1892	1588
Perryman No. 5	6397	6000	6171
Churchville C	339	527	648
Churchville B	1130	1064	1080
ATEF Paved	76	122	158
ATEF Gravel	265	522	736
Churchville B Smooth	556	700	815
Churchville B Rough	2195	1721	1539

TABLE 3. SUMMARY OF ATC COURSE STATISTICS

COURSE NAME	STANDARD DEVIATION, in.	SKEWNESS	KURTOSIS	80% RANGE, in.
3-Mile Straight-away	0.13	-0.47	9.77	0.30
Belgian Block	0.76	-0.06	3.52	1.91
Improved Gravel Road	0.42	-0.19	4.71	1.01
Perryman A	0.61	-0.31	5.39	1.43
Perryman No. 1	0.60	-0.30	12.93	1.41
Perryman No. 2	1.25	0.09	5.84	2.94
Perryman No. 3	5.65	1.15	4.93	12.42
Perryman No. 5	3.12	0.22	2.57	8.27
Churchville C	0.38	0.18	18.41	0.68
Churchville B	3.09	2.08	13.50	4.58
ATEF Paved	0.08	-0.21	5.80	0.18
ATEF Gravel	0.21	0.58	7.27	0.49
Churchville B Smooth	1.07	0.77	14.27	1.84
Churchville B Rough	5.03	1.36	5.51	11.95

TABLE 4. SUMMARY OF ATC GRADES

COURSE NAME	GRADE (%)	
	Max	Std. Dev.
3-Mile Straight-away	1.1	0.4
Belgian Block	3.9	1.6
Improved Gravel Road	3.3	1.2
Perryman A	1.9	0.5
Perryman No. 1	3.5	0.8
Perryman No. 2	5.9	1.6
Perryman No. 3	8.0	2.3
Perryman No. 5	2.2	0.7
Churchville C	11.2	5.0
Churchville B	29.3	9.9
ATEF Paved	0.7	0.4
ATEF Gravel	1.0	0.4
Churchville B Smooth	29.3	9.7
Churchville B Rough	23.2	10.1

5.1.2 <u>3-Mile Straight-away</u>.

This is a continuous asphalt course located in the PTA, consisting of a 5 km (3 miles (mi)) straightway with banked turnaround loops at each end for tests requiring uninterrupted operations such as cooling tests, operation at high speed, etc. The course has a speed limit of 80 km/hr (50 mph) on the straight section (which may be exceeded by written waiver) and 40 km/hr (25 mph) in the turnaround loops. While this course is frequently used for endurance and performance testing, the course is not frequently profiled due to the expectation that the profile of a paved course does not change very quickly. A representative WNS of this course is presented in Figure 1.

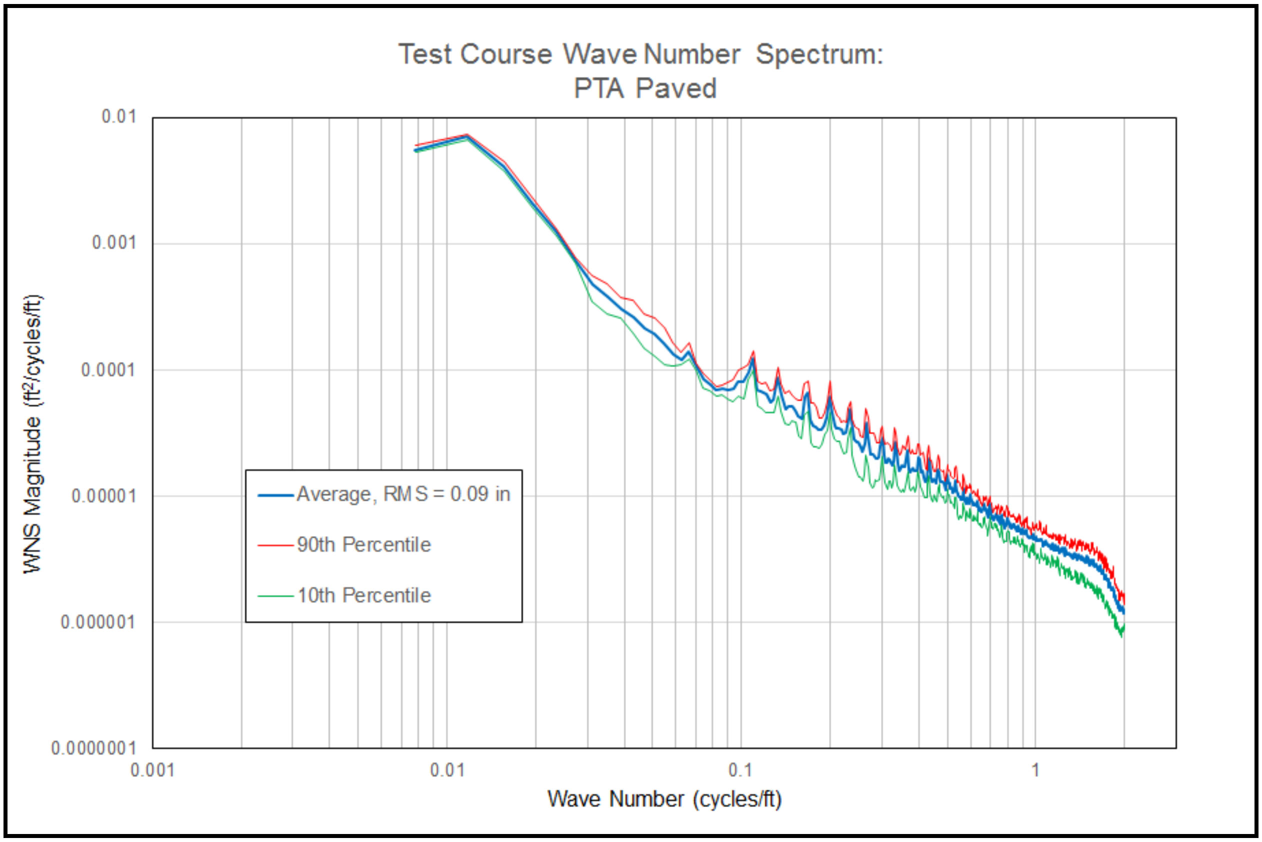

Figure 1. Wave Number Spectrum of Perryman Paved Course.

5.1.3 Munson Improved Gravel Road.

This road in the MTA is a loop of about 3 km (2 mi) with left and right curves, and some distinct straight sections, with a noticeable crown. The surface is compacted “Bank Run” gravel, maintained by grading. Frequently portions of this course are used to form a contiguous loop with other courses in the MTA, such as when a vehicle runs the Gravel – Belgian Block loop. The typical operational speed limit is 56 km/hr (35 mph). The nominal RMS of the course is 0.25 in., though that is likely to vary greatly throughout a year given exposure to inclement weather and high mileage wear exposure from a variety of vehicles. The WNS of Munson Improved Gravel is presented in Figure 2.

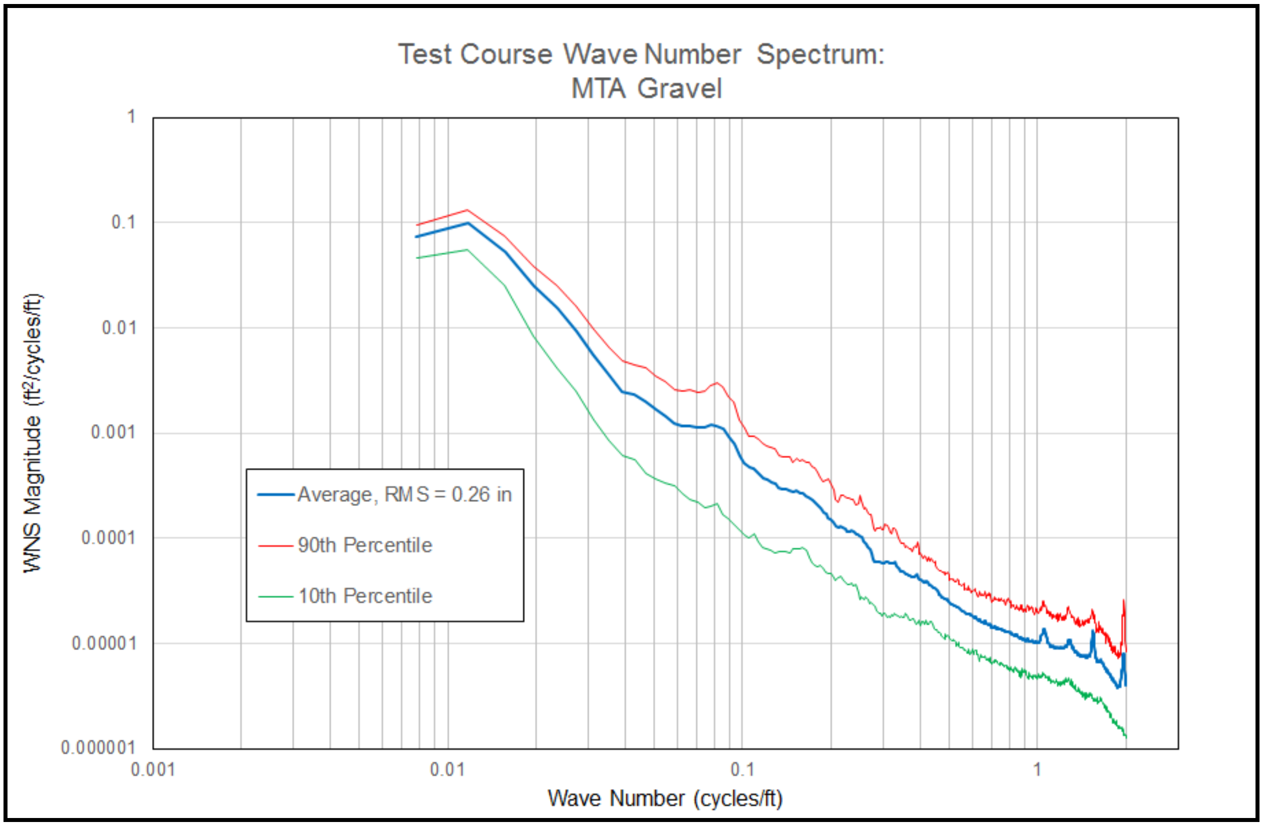

Figure 2. Munson Gravel Course spectrum.

5.1.4 <u>Perryman A Course</u>.

This is a generally level course used for tests of various types of vehicles, with frequent useage by tracked vehicles, consisting of a 3.9-km (2.4-mi) loop. This road has sharp and sweeping turns typical of unimproved country roads. A distinct straight section runs parallel to the 3-Mile Straight-away. The course is maintained by grading and filling with native soil. Under wet conditions, severe mud is present; when dry, the course is extremely dusty. The typical operational speed limit is 56 km/hr (35 mph). The WNS of this course is presented in Figure 3.

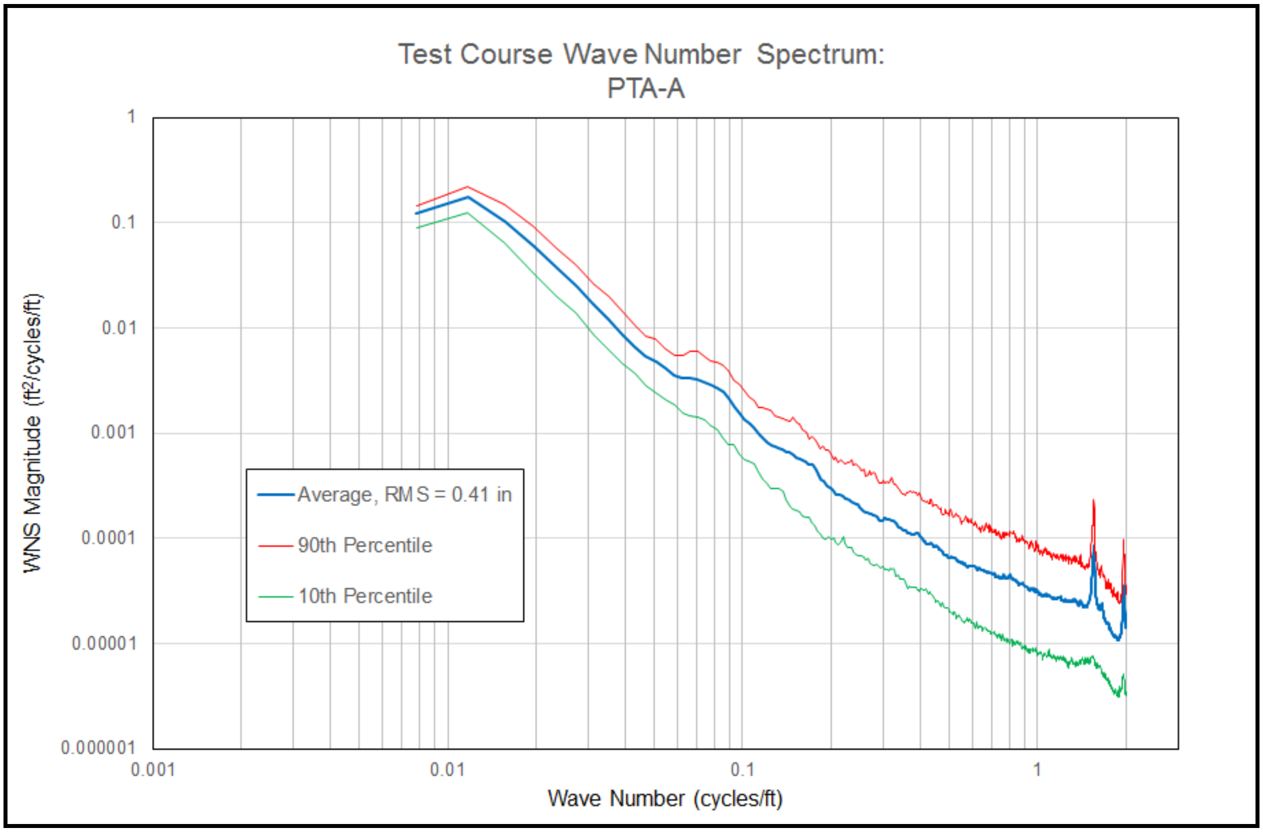

Figure 3. Perryman A Course spectrum.

5.1.5 Perryman No. 1 Course.

This is a generally level course of moderate irregularity with a substantial roadbed primarily of quarry spall and bank run gravel. The 8.4-km (5.2-mi) loop contains both sharp and sweeping curves, with a distinct straight section parallel to the 3-Mile Straight-away. The surface ranges from smooth to rough; roughness is due to potholes, washboard, and rutting. Potholes and other sharp depressions are limited in depth by filling in with crushed stone. The typical operational speed limit is 56 km/hr (35 mph). The WNS of this course is presented in Figure 4.

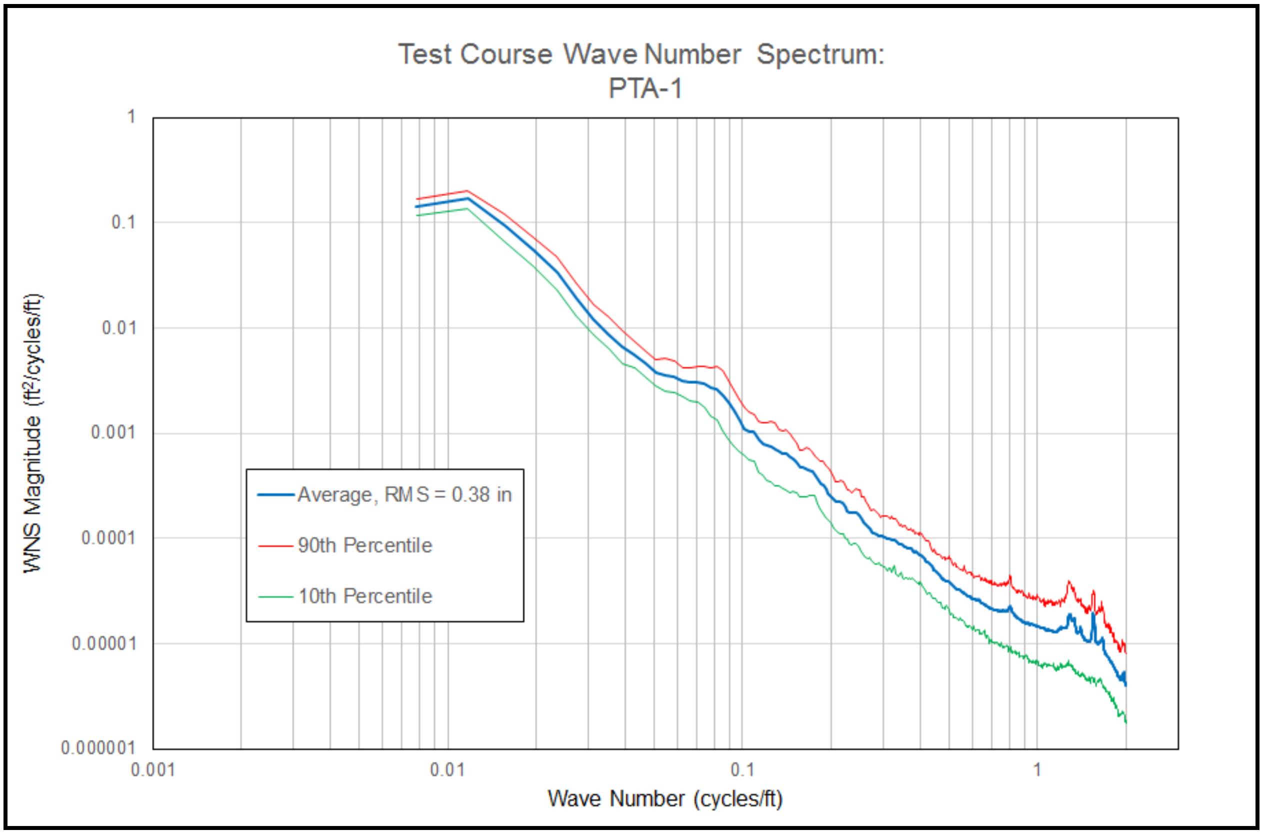

Figure 4. Perryman No. 1 Course spectrum.

5.1.6 Perryman No. 2 Course.

This course is laid out in a loop of moderately irregular terrain. Surfaces range from smooth to rough, with sweeping turns resulting in a 2.9-km (1.8-mi) loop. Perryman No. 2 is not as level as Perryman A or Perryman No. 1, but has relatively mild grades when compared to Churchville Test Area courses or many YTC courses. The course is made up of loose native soil. A mixture of soil and stone is used to fill in holes during maintenance. Wear and weather can lead to some stone exposure. Under wet conditions, severe mud is present; when dry, the course is extremely dusty. The typical operational speed limit is 40 km/hr (25 mph). The WNS of this course is presented in Figure 5.

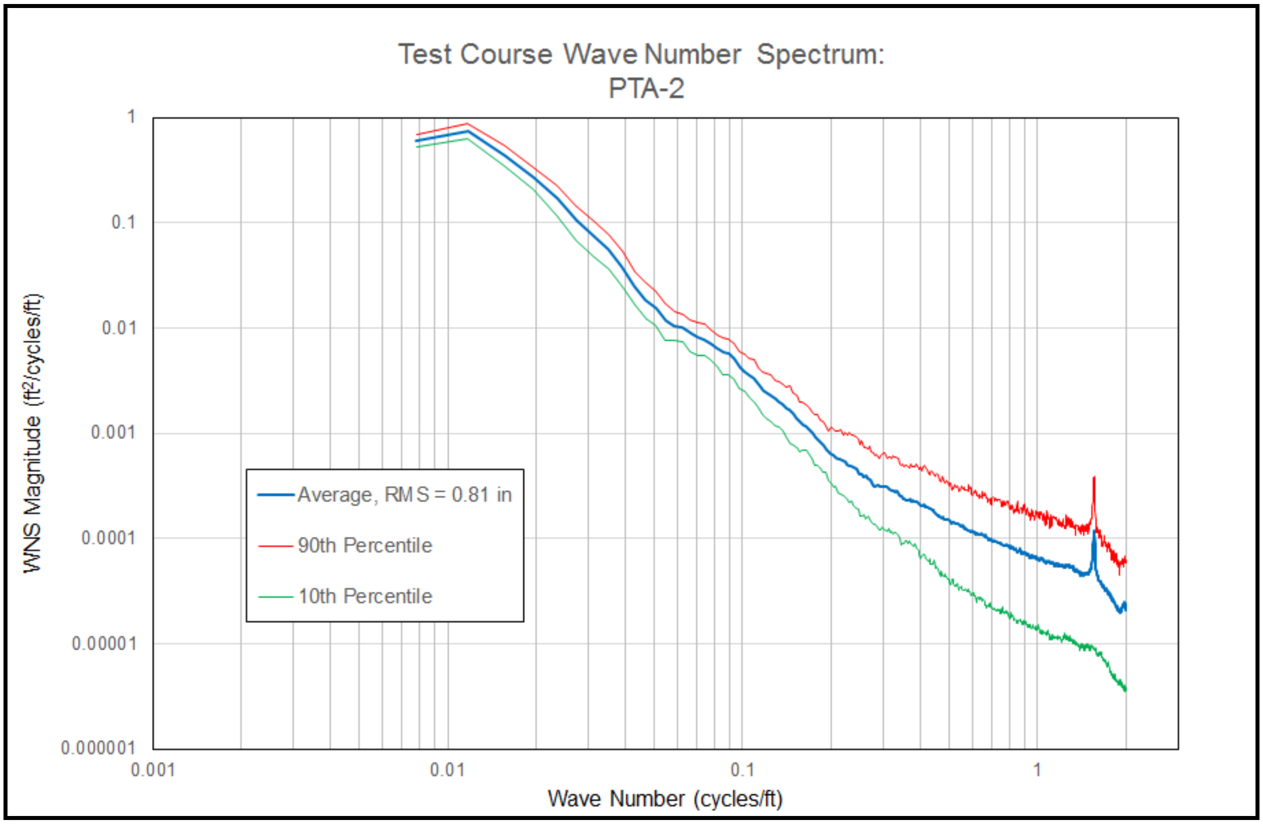

Figure 5. Perryman No. 2 Course spectrum.

5.1.7 Perryman No. 3 Course.

This is a rough course of native soil similar to the soil of Perryman No. 2 Course. Mud ranges from light (with free water) to cohesive. Under wet conditions, severe mud is present; when dry, the course is extremely dusty. The courses consists of approximately 74 humps with an average peak-to-peak spacing of 61 m (200 ft), with spacing's ranging from approximately 37 m (120 ft) to 90 m (295 ft) apart. The humps have a typical height of about 1 m (3 ft), with possible heights ranging from 0.5 m (1.5 ft) to 1.4 m (4.5 ft). The roughness between the humps is generally comparable to that of Perryman No. 2. However, a notable characteristic is that the Average IRI value for Perryman No. 3 increases as speed increases (unlike most other courses, such as Perryman No. 2). The typical operational speed limit is 32 km/hr (20 mph). The WNS of Perryman No. 3 Course is presented in Figure 6.

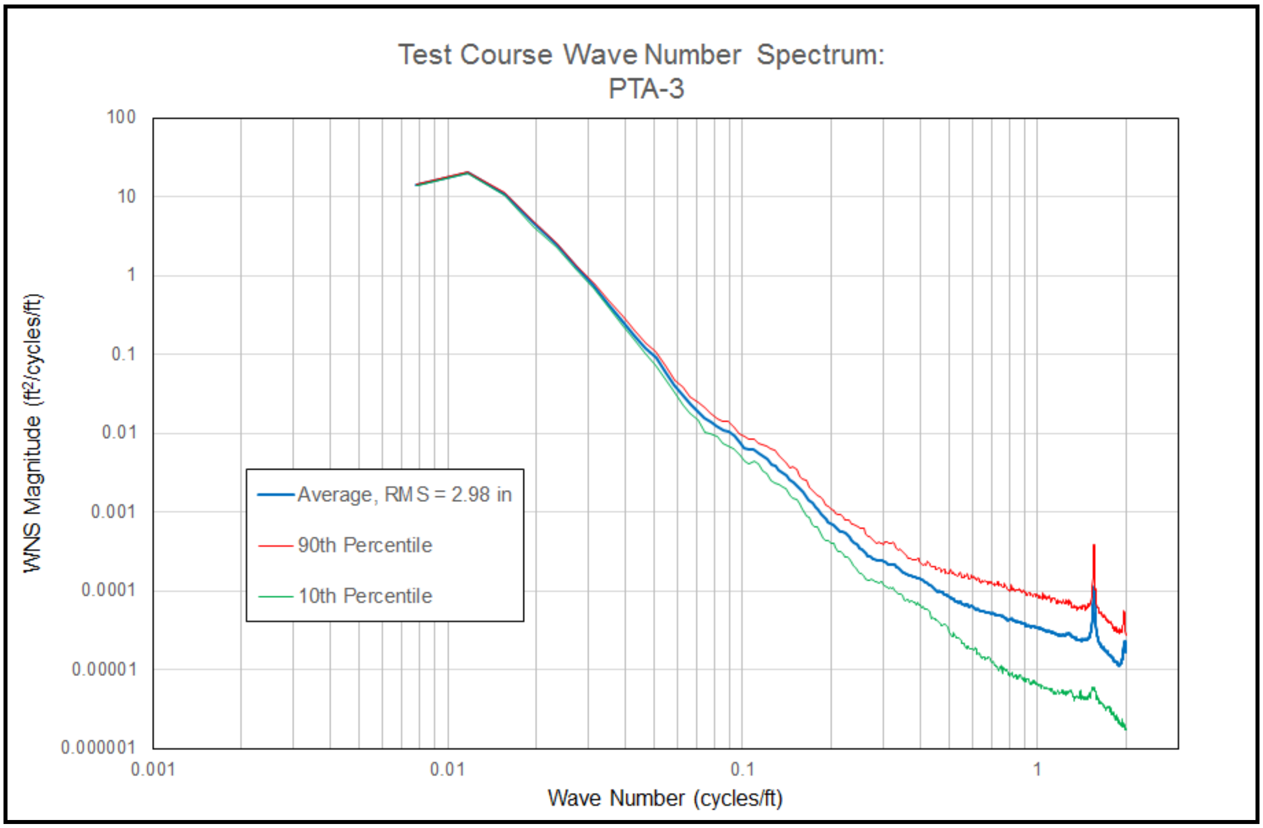

Figure 6. Perryman No. 3 Course spectrum.

5.1.8 Perryman No. 4 Course.

This is a tract of native soil making up extremely rough terrain including marshy areas with swamp-type vegetation. The profile is a series of main repetitive humps spaced in a pattern. The swampy and deformable nature of the soil means maintenance must be a concerted effort. The extreme marshy character and vegetation make profile measurements impossible. Therefore a wave number spectrum is not available.

5.1.9 Perryman No. 5 Course.

This is a relatively level and straight course, 300 m (1000 ft) in length, intended to be extremely rough which causes large suspension displacements at slow speeds. Constructed from gravel and large stone, Perryman No. 5 was originally built to be a mobility course, though later reconstruction iterations allowed the course to be used for endurance testing. The course is intentionally built to induce roll inputs by having the “left” side be out of phase relative to the “right” side. Maintenance of this course requires concerted effort because of the large amplitude changes within short distances. The course is not used for endurance testing as frequently as the other test courses, therefore it is not profiled as frequently. Operational speeds are typically set through jury rides prior to testing to take into account course conditions at the time of the test. Typically speeds are 25 km/hr (15 mph) or less. Relative to other courses, Perryman No. 5 contains more spectral content in the 1.5 m (5 ft) to 9 m (30 ft) wavelength range. The WNS presented in Figure 7 should only be used to give a sense of the nominal roughness.

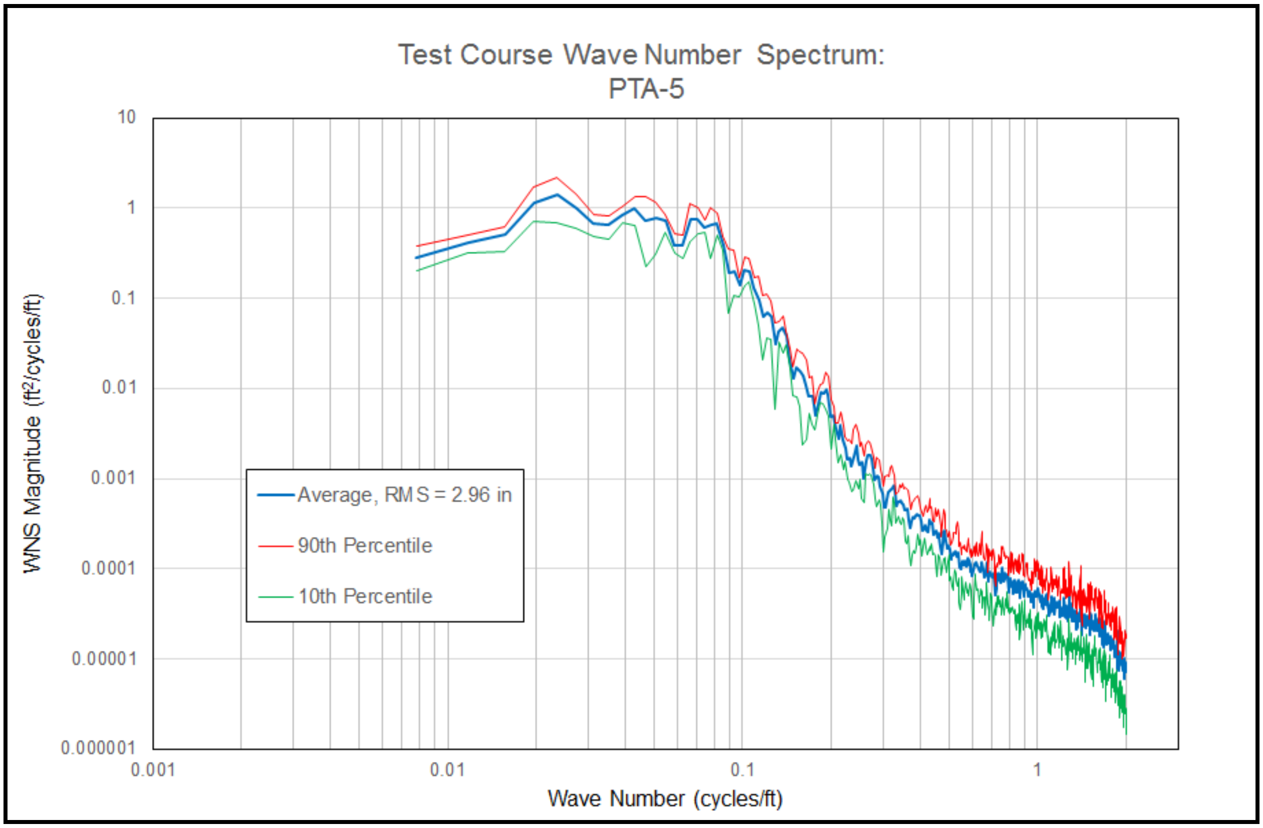

Figure 7. Perryman No. 5 Course spectrum.

5.1.10 Churchville B Course.

This course consists of broad and tight turns making a 5.8-km (3.6-mi) loop. The course has a wear surface of “Bank Run” gravel that is similar to Munson Improved Gravel Road. Some of the turns occur at the base of hills, causing additional stresses on the vehicles. This course contains the most severe grades at ATC, with the largest grade of 29 percent. Churchville B Course also has the most frequent grade changes along course length, with the transitions between grades (cresting, leveling off, etc.) being more abrupt relative to other courses. Stop signs are located at various locations around the course which causes more severe loading on brake systems and on power trains as the vehicle must regain momentum to climb the hills.

a. The course contains an approximately 1 mile long “rough” section, which consists of approximately 37 “hump” features. Because many of the humps are built onto the grades, the “peak” of a hump is not necessarily higher than any part of the course further up the hill. Instead, the elevation profile of the humps on downward grades feature a brief segment of leveling off followed by a brief segment of steeper grade. The humps have a nominal length of 12 m (40 ft) to 15 m (50 ft). The hump features become more apparent when a profile is processed with a high pass filter to remove the elevation of the hill, with hump heights ranging from approximately 0.4 m (1.2 ft) to 0.8 m (2.6 ft). The rough section also has the characteristic of the average IRI increasing as speed increases, caused by the humps inducing more suspension movement as the vehicle moves faster. The remainder of the Churchville B (the “smooth” section) has average IRI responses comparable to Perryman No. 1.

b. The typical operational speed limit is 56 km/hr (35 mph), with an expectation that reducing speeds in the “rough” section may be necessary. The WNS of just the “rough” section of Churchville B Course is presented in Figure 8, while the WNS of the entire course is presented in Figure 9.

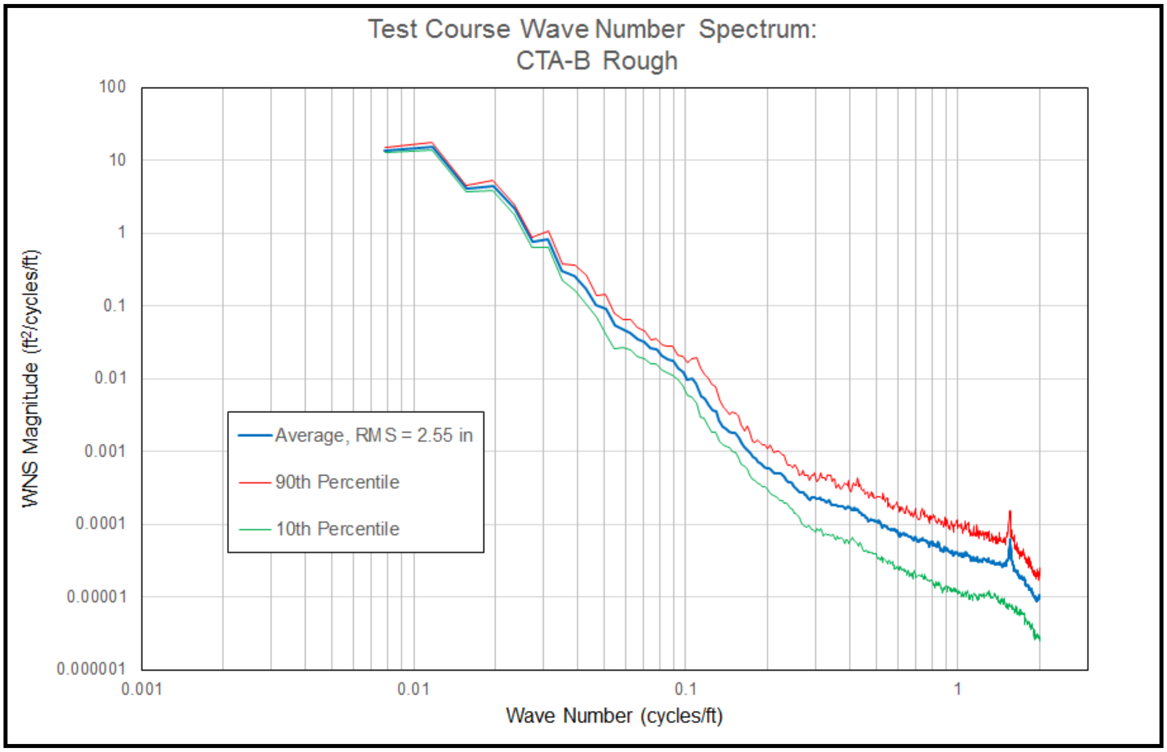

Figure 8. Churchville B Course, "rough" section spectrum.

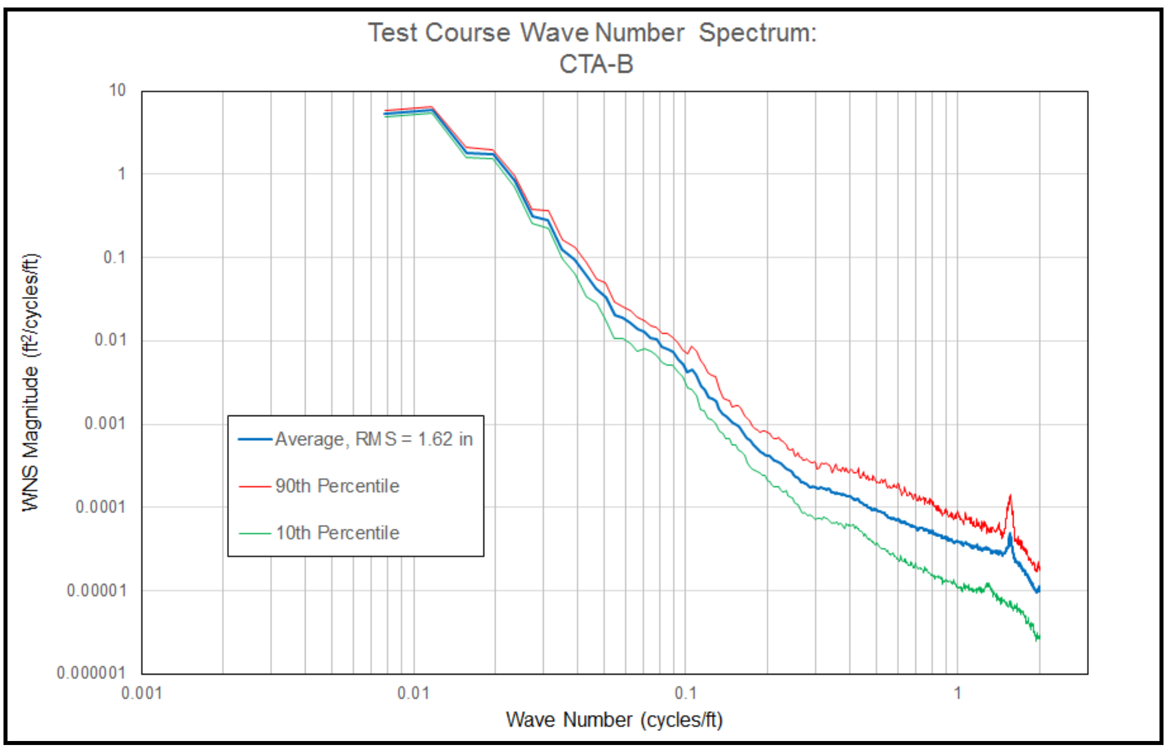

Figure 9. Churchville B Course, entire course spectrum.

5.1.11 Churchville C Course.

Churchville C Course is a 2.4-km (1-1/2-mi) secondary road test course with long consistent grades up to 10 percent and turnarounds at each end. The wear surface consists of “crusher run” gravel and is generally free of significant ruts or potholes. WNS of Churchville C Course is comparable that of the Munson Improved Gravel road, primarily because the grades are sustained for such long durations with milder transitions at the top of the grades. The IRI values of Churchville C are also comparable to Munson Improved Gravel road. The typical operational speed limit is 56 km/hr (35 mph), with a reduced speed of 32 km/hr (20 mph) in the turnarounds. The WNS of Churchville C Course is presented in Figure 10.

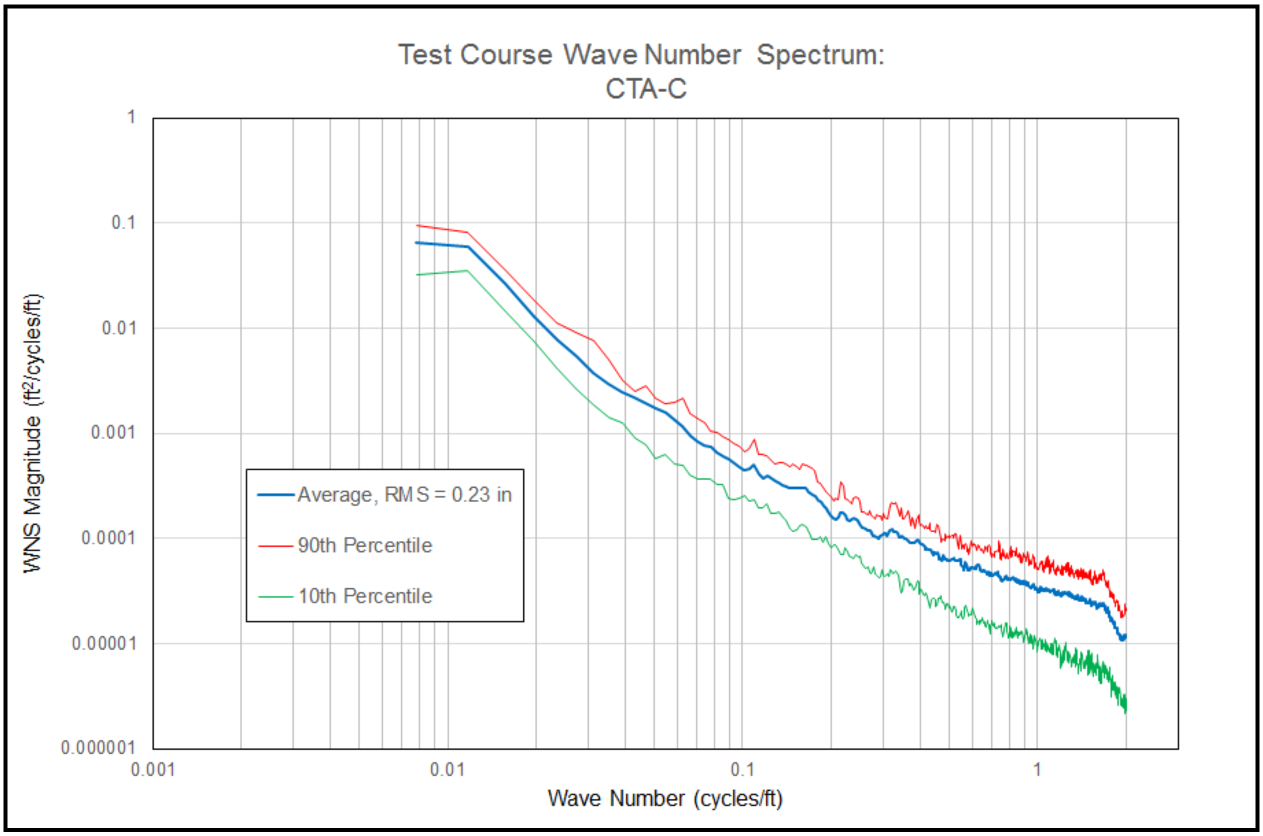

Figure 10. Churchville C Course spectrum.

5.1.12 Belgian Block.

a. This is a paved course with unevenly laid granite blocks imbedded in concrete and mortar, forming an undulating surface. It duplicates a rough cobblestone road such as is found in many parts of the world. The course, which is about 1.2 km (0.75 mi) long, does not form a complete loop. Endurance testing is typically done by forming a loop by using a section of Munson Improved Gravel Road. The Belgian Block course contains two turns on the north side, an approximately 560 m (1,800 ft) straight section, followed by more turns on the south side. The course is useful as a standard rough road for accelerated tests of wheeled vehicles. It is generally included in cycles of courses used for vibration studies. The motion imparted to a vehicle is a combination of roll and pitch and high frequency vibrations.

b. The WNS of the Belgian Block Course is presented in Figure 11. The peak at 0.269 cycle/m (0.082 cycle/ft), a wavelength of 3.7 m (12.2 ft), indicates periodic undulation at this frequency. The typical operational speed limit is 40 km/hr (25 mph), with the expectation that speeds may need to be reduced in the turns.

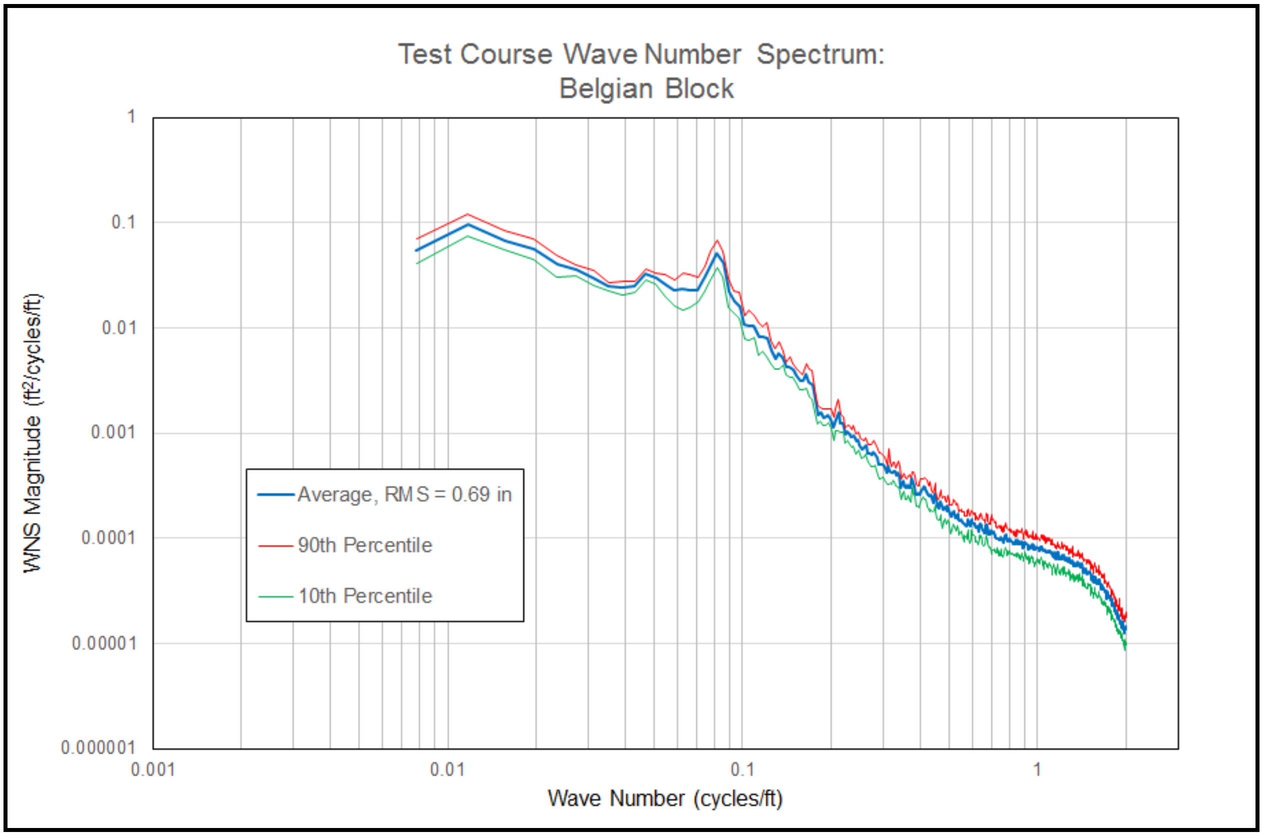

Figure 11. Belgian Block spectrum.

5.1.13 ATEF Paved.

ATEF Paved road is a generally level paved course consisting of some straight sections and some broad turns to form a 7.2-km (5.2 mi) long loop. The road has a wear surface similar to highway surfaces in good condition. The purpose of the course is to enable testing at sustained high speeds. The maximum test course speed is 112 km/hr (70 mph). The WNS of ATEF Paved is presented in Figure 12.

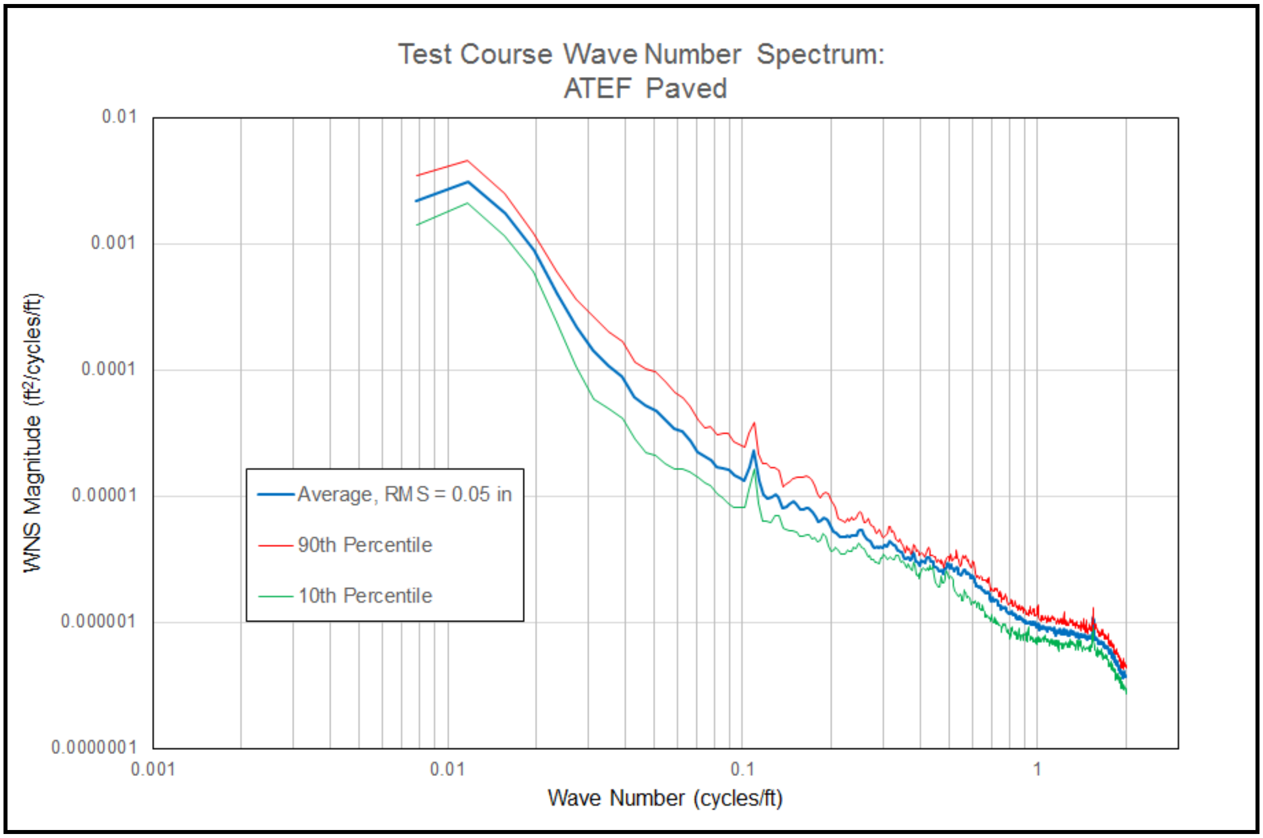

Figure 12. ATEF Paved spectrum.

5.1.14 <u>ATEF Gravel</u>.

The ATEF Gravel course runs alongside ATEF Paved (exterior to the loop), separated by a small grass strip. ATEF Gravel has no significant crowning and has a wear surface of "Bank Run" gravel. The purpose of the course is to enable testing at sustained high speeds on a gravel wear surface. The maximum test course speed is 80 km/hr (50 mph). The WNS of ATEF Gravel is presented in Figure 13.

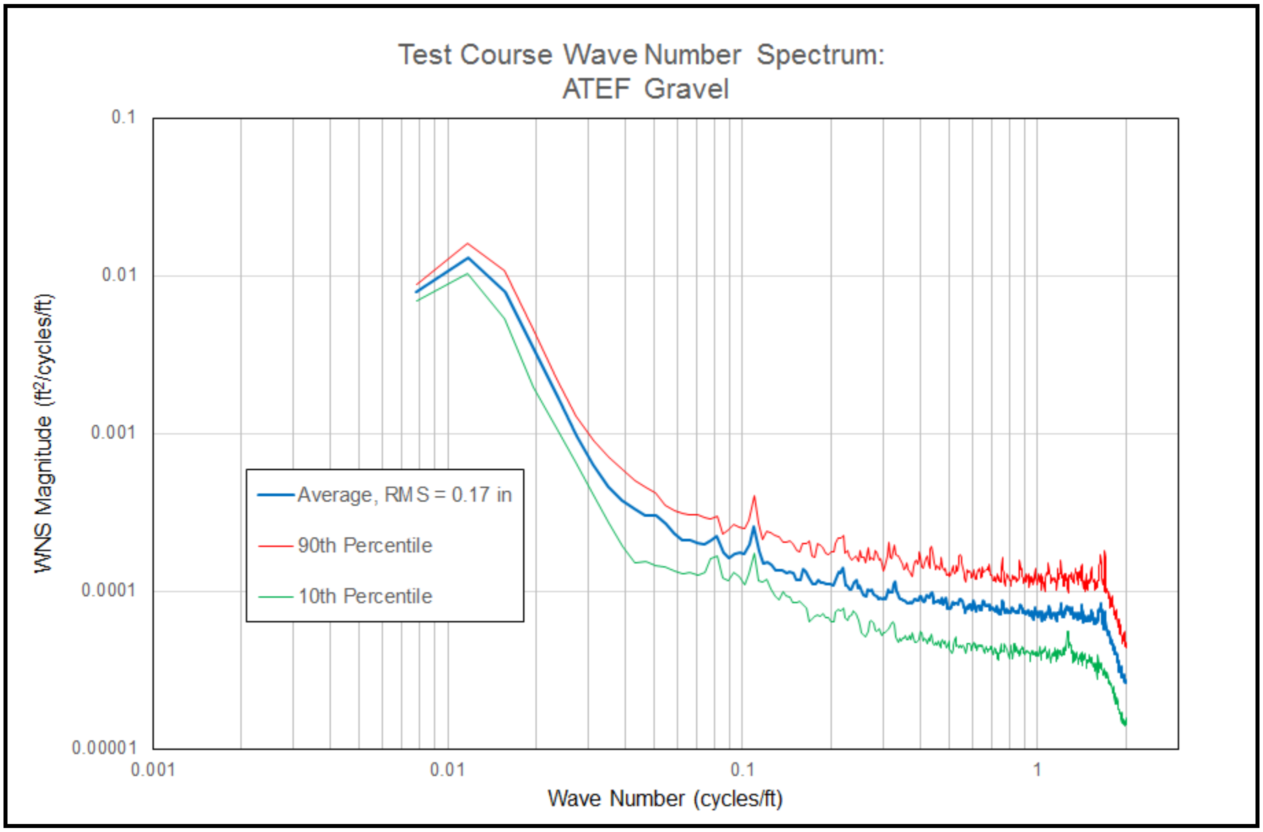

Figure 13. ATEF Gravel spectrum.

5.1.15 Overlay of ATC Test Courses.

The average wave number spectra for most of the ATC courses described above are combined and presented in Figure 14.

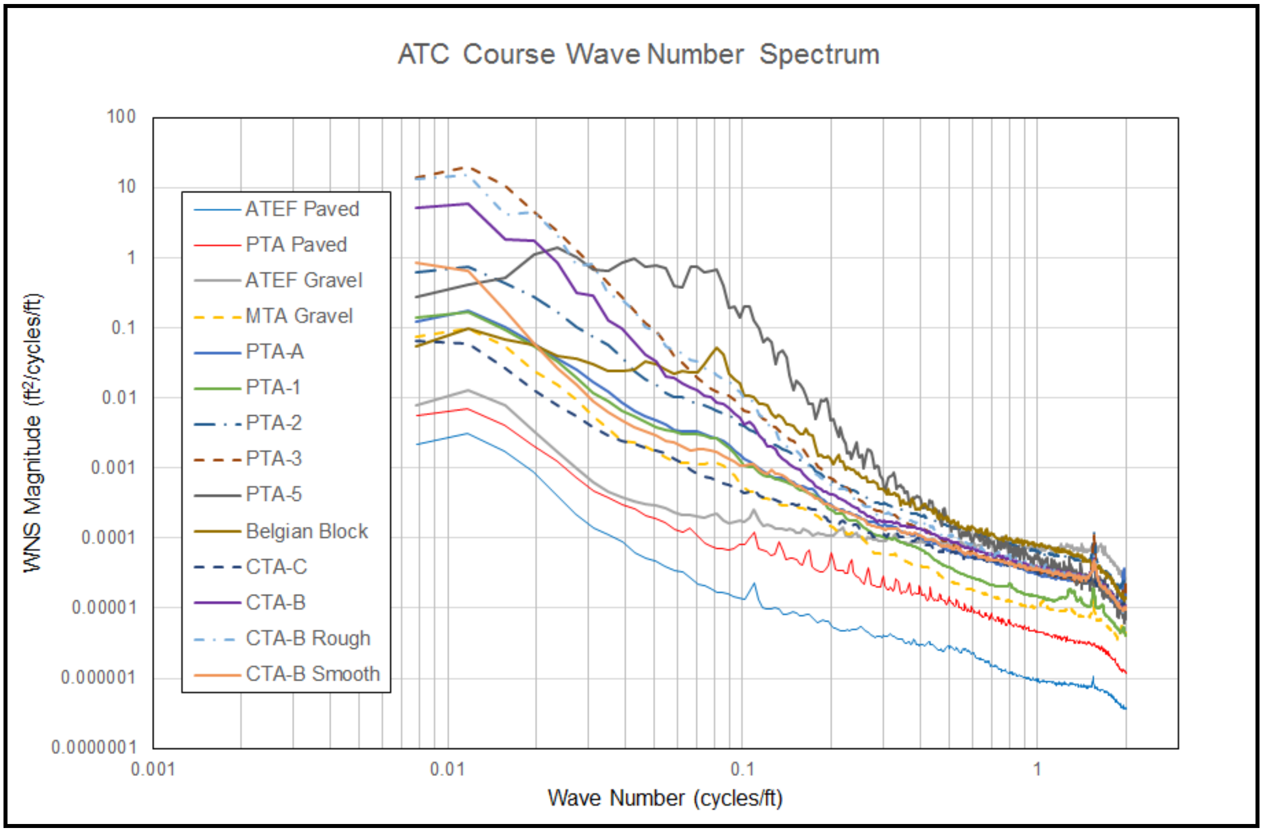

Figure 14. Overlay of ATC Endurance Test Courses.

5.2. Yuma Test Center (YTC) Courses.

5.2.1 Summary.

The statistics for the surface profile terrain severity were calculated for each endurance course at YTC and are presented in this section. Five values are presented for course RMS: The average over the entire course (from approximately 10 data samples); the standard deviation of those data samples; and, to show the variability of RMS within the courses, the minimum, maximum, and standard deviation of the RMS for 1,024-ft sections of the course (using Welch's method with a 256-foot block-size and 252-foot overlap). Note that some of the added statistics for YTC's courses are presented due to the generally higher variability present in YTC's automotive test courses. The statistics are defined as follows:

a. RMS (Table 5 and Figure 15).

TABLE 5. YTC COURSE RMS STATISTICS

COURSE NAME	RMS (in.)		1,024-FT SECTION RMS (in.)		
	Average	Std. Dev.	Min	Max	Std. Dev.
Desert March	1.13	0.03	0.23	3.15	0.56
Kofa High-Speed Gravel	0.11	0.04	0.08	0.27	0.04
Kofa Level Gravel	0.17	0.01	0.09	0.30	0.05
Laguna High-Speed Paved	0.04	0.00	0.02	0.08	0.01
Laguna Hilly Trails	0.56	0.09	0.30	0.91	0.15
Laguna Hilly Trails Short Course	0.50	0.06	0.28	0.71	0.12
Laguna Level Trails East	0.41	0.01	0.27	0.68	0.09
Laguna Level Trails West	0.52	0.02	0.22	0.90	0.15
Laguna Paved	0.07	0.00	0.03	0.18	0.03
Middle East	2.01	0.09	0.25	4.70	1.01
Patton Hilly Gravel	0.51	0.02	0.31	0.85	0.11
Patton Hilly Trails	1.70	0.05	0.56	3.09	0.63
Patton Level Gravel	0.47	0.09	0.21	0.91	0.16
Patton Level Trails	1.02	0.05	0.28	2.08	0.40
Rock Ledge	1.56	0.02	0.42	2.77	0.60

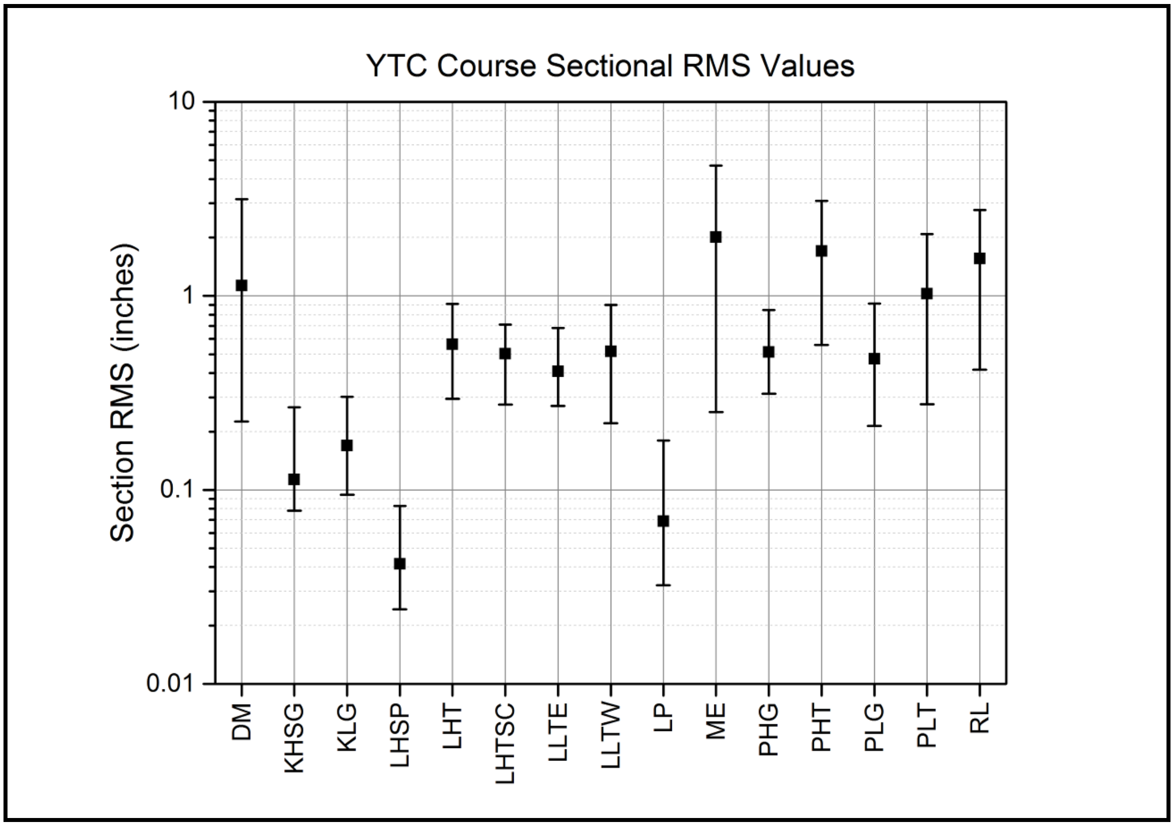

Figure 15. YTC Course RMS values (average, minimum, and maximum from 1,024-foot sections).

(1) Average normal displacement RMS over the entire course (taken over approximately a dozen profiles).

(2) Standard deviation of the course RMS, a measure of the variance over time (taken over approximately a dozen profiles).

(3) Minimum sectional RMS of the course, when broken up into 1,024-foot sections (averaged over at least three profiles).

(4) Maximum sectional RMS of the course, when broken up into 1,024-foot sections; maximum RMS is significant in that this is the roughest expected terrain (averaged over at least three profiles).

(5) Standard deviation of the 1,024-foot sectional RMS values (a measure of the variance in roughness over the course) (averaged over at least three profiles).

b. International Roughness Index (IRI) (Table 6).

TABLE 6. YTC COURSE IRI STATISTICS

COURSE NAME	AVERAGE IRI (inches / mile)			SECTION IRI, 50 MPH (inches / mile)		
	50 mph	25 mph	15 mph	Min	Max	Std Dev
Desert March	1054	1347	1527	425	2445	361
Kofa High-Speed Gravel	205	496	579	143	332	44
Kofa Level Gravel	318	708	928	206	560	78
Laguna High-Speed Paved	47	61	76	32	64	8
Laguna Hilly Trails	871	1161	1272	461	987	132
Laguna Hilly Trails Short Course	692	915	1011	412	873	116
Laguna Level Trails East	560	661	753	478	797	64
Laguna Level Trails West	623	797	879	409	1146	157
Laguna Paved	73	83	92	38	169	28
Middle East	1664	1759	1905	316	3422	622
Patton Hilly Gravel	747	1226	1518	437	1132	127
Patton Hilly Trails	1423	1190	1118	826	2541	416
Patton Level Gravel	659	811	850	292	1007	150
Patton Level Trails	1049	1198	1156	379	2548	375
Rock Ledge	2200	2942	3296	675	4378	1010

(1) IRI, being a velocity-dependent parameter, is presented at three speeds: the standard IRI speed of 80 km/hr (49.7 mph), a speed of 40 km/hr (24.9) mph, and a speed of 25 km/hr (15.5 mph).

(2) Additionally, the course was broken up into 1,024-foot sections to observe how IRI varied throughout each course. The minimum, maximum, and standard deviation of the 50 mph IRI is presented for the 1,024-foot sectional course.

c. Grade (Table 7).

TABLE 7. YTC COURSE GRADE STATISTICS

COURSE NAME	GRADE (%)	
	Max	Std. Dev.
Desert March	24.1	3.4
Kofa High-Speed Gravel	2.3	0.9
Kofa Level Gravel	1.8	0.9
Laguna High-Speed Paved	1.3	0.8
Laguna Hilly Trails	23.7	8.3
Laguna Hilly Trails Short Course	11.3	3.6
Laguna Level Trails East	9.5	3.1
Laguna Level Trails West	9.8	2.9
Laguna Paved	1.6	0.8
Middle East	30.8	5.0
Patton Hilly Gravel	26.0	8.0
Patton Hilly Trails	31.7	11.3
Patton Level Gravel	7.2	1.6
Patton Level Trails	16.2	3.0
Rock Ledge	15.4	4.0

(1) Maximum grade in either direction of the course is presented as it represents the most difficult grade a vehicle would negotiate on the course. Since maximum grade is often presented as a system requirement and/or performance limitation, test planning should include consideration that this parameter does not exceed the capabilities of the vehicle system.

(2) Standard deviation of the grade can be considered a measure of the average grade on the course. A higher average standard deviation indicates a higher proportion of hilly terrain. Hilly courses at YTC are those that are considered to have a standard deviation of the grade greater or equal to 5%. Note that the standard deviation is equal to RMS of the grade, since all courses start and end at the same elevation (zero mean grade).

5.2.1 Laguna Paved (LP).

The Laguna Paved Course is a 3.6 km (2.25-mile), smooth, near-level (0.8-percent grade), single-lane roadway with 152-meter (500-ft) radius turnarounds at each end, surfaced with high-strength asphalt. Performance and durability tests of vehicles are performed on this course. The wave number spectrum is presented in Figure 16.

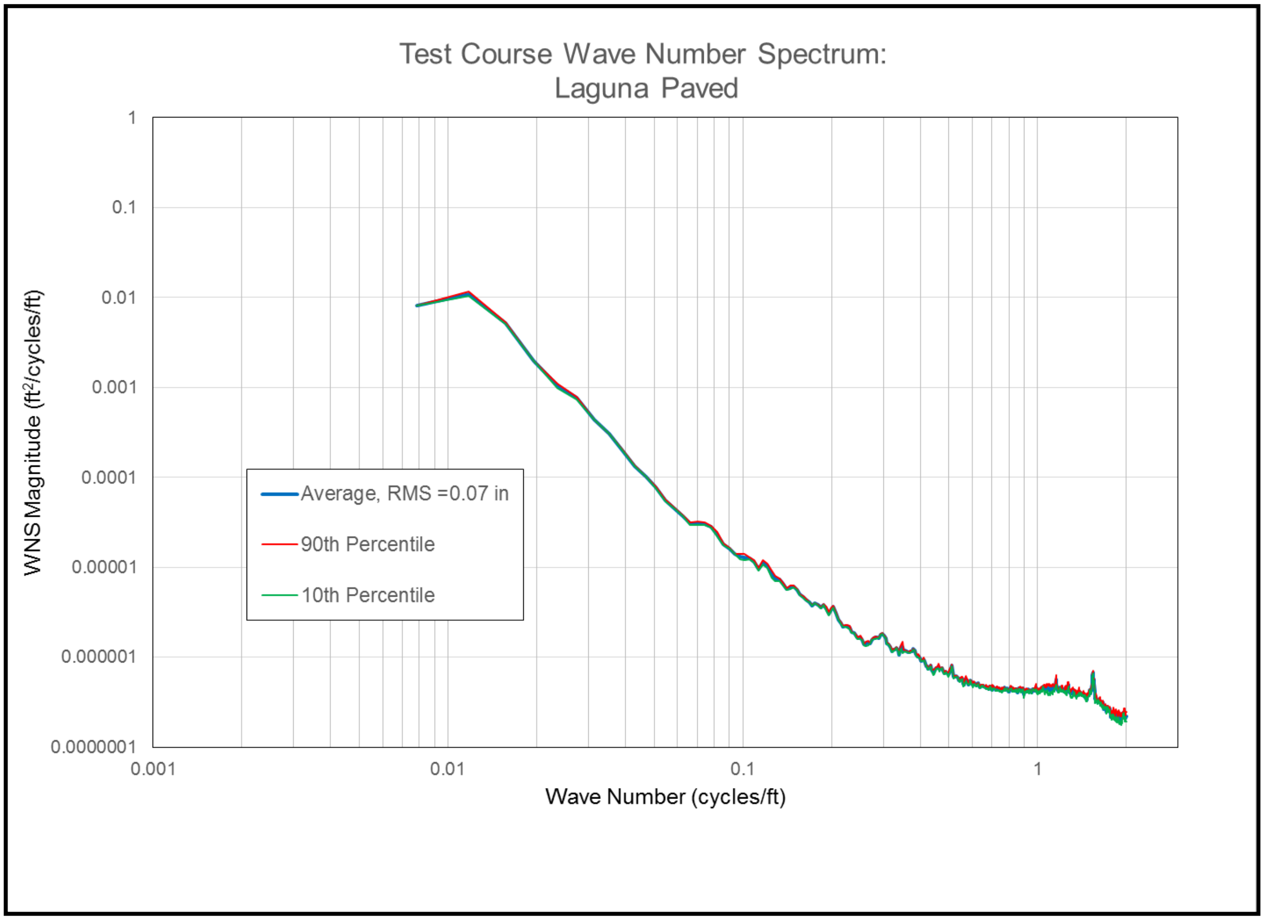

Figure 16. YTC Laguna Paved Course WNS.

5.2.2 Laguna High-Speed Paved (LHSG).

The Laguna High-Speed Paved Course is a two-lane, 7.3 km (4.5 mi), smooth, near-level (0.8-percent grade), oval roadway with 2.4 km (1.5 mi) straightaways and 366-meter (1200-ft) banked radius turns at each end, surfaced with high-strength asphalt. Performance and durability tests of vehicles are performed on this course. The wave number spectrum is presented in Figure 17.

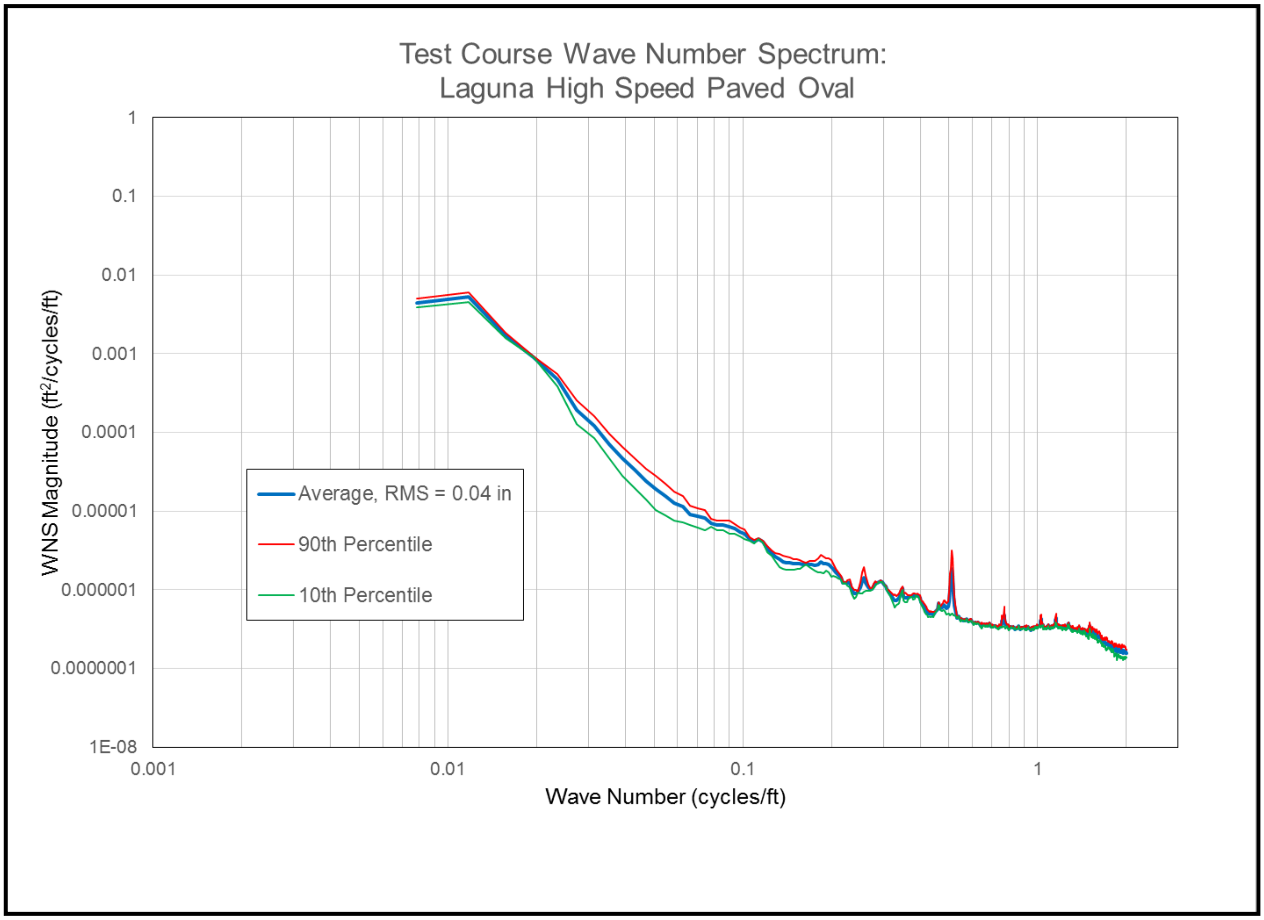

Figure 17. YTC Laguna High-Speed Paved Course WNS.

5.2.3 Kofa Level Gravel (KLG).

This course is designed to represent an improved secondary gravel road. The course is a nearly level (~1.0% grade on the straightaways) oval loop 5 km (3.1 mi) long and 12 m (40 ft) wide, with 1.25-mile straightaways and 500-ft radius turns. The course is composed of quarried road construction grade gravel that has been compacted and graded. KLG, as a high-speed secondary road, exhibits a strong washboard effect at wave numbers of 0.3 to 0.5 cycles per foot; the washboard is graded when the wave number spectrum amplitude approaches 5.0×10^{-3} $feet^2$/(cycles/foot). The wave number spectrum is presented in Figure 18.

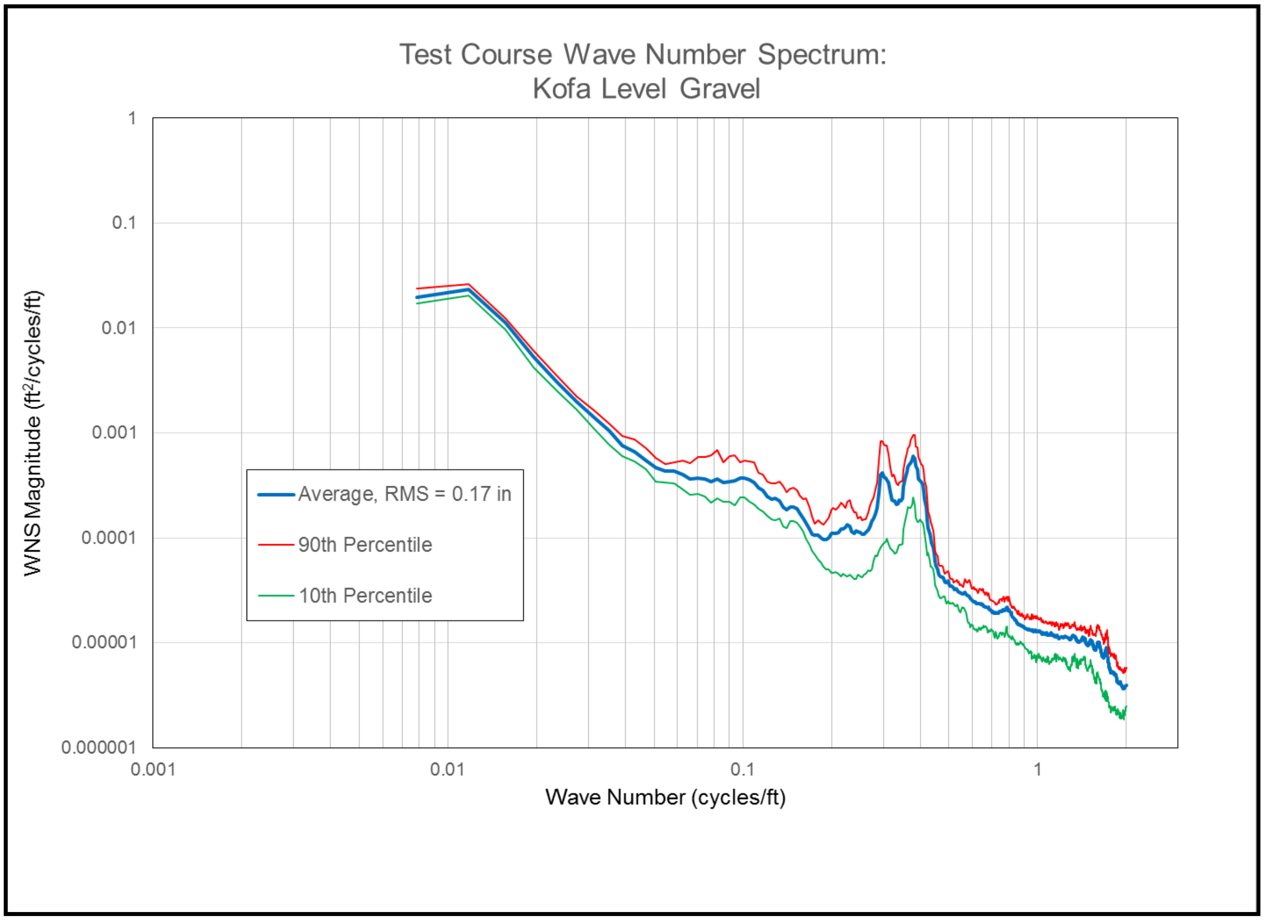

Figure 18. Kofa Level Gravel Course WNS.

5.2.4 Kofa High-Speed Gravel (KHSG).

Kofa High-Speed Gravel is an enlargement of Kofa Level Gravel intended for higher speed operations, with 1.3-mile straightaways and 1,300-foot radius turns. KHSG also presents a strong washboard effect during the peak of the washboard cycle. The wave number spectrum is presented in Figure 19.

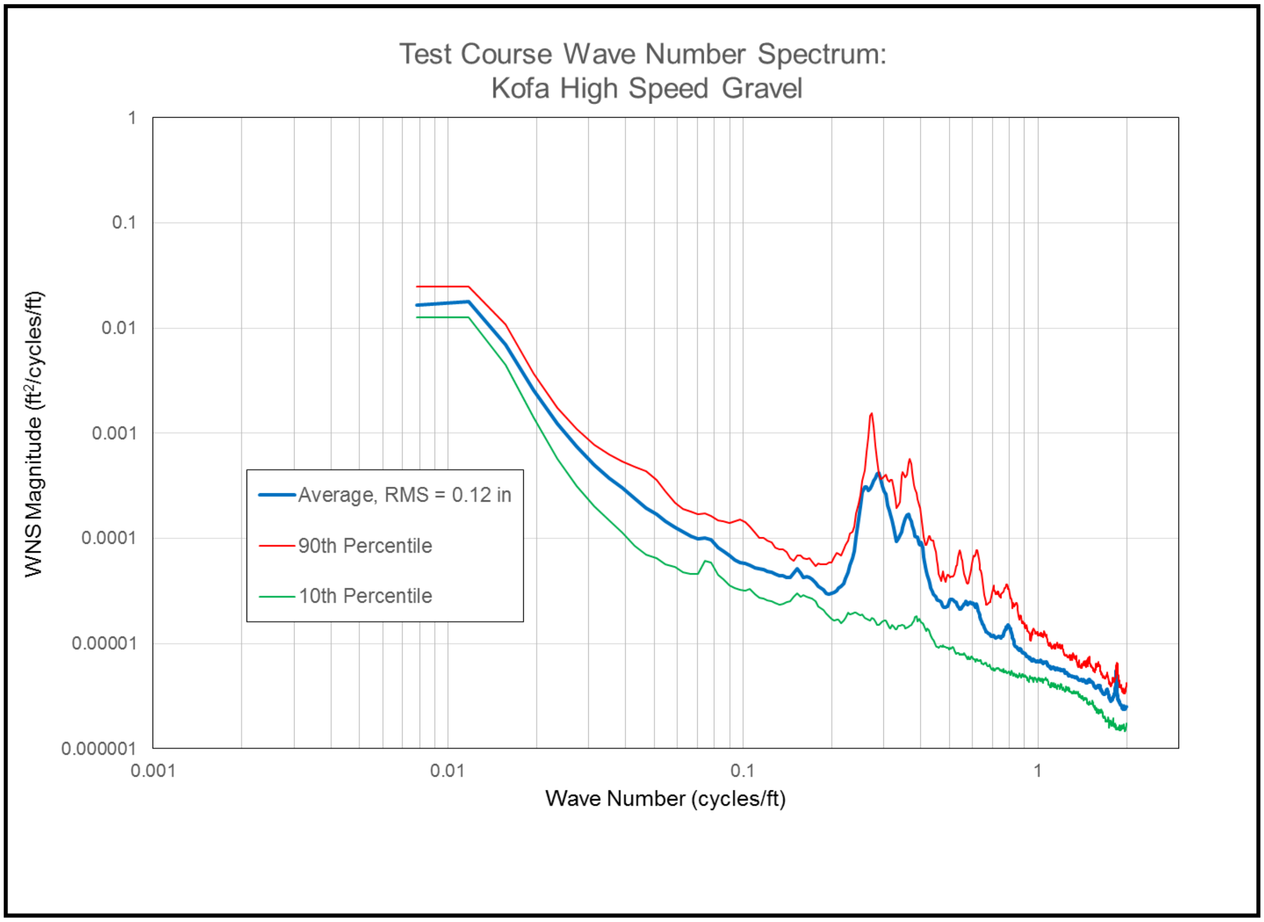

Figure 19. Kofa High-Speed Gravel Course WNS.

5.2.5 Patton Level Gravel (PLG).

Patton Level Gravel is a 5.8 km (3.6 mi) loop with a surface of quarried road construction grade gravel that has been compacted and graded. The four landforms that the Patton Level Gravel course crosses are dissected fan, alluvial fan, alluvial terrace, and sand dune. The course is used for testing track-laying vehicles and heavy trucks under conditions similar to a secondary graveled road. The course consists of short, straight sections and curves of varying radii, which provide a test of steering mechanisms at medium vehicle speeds. (Note that the WNS spikes at high wave numbers correspond to track imprints in the sandy sections of the course, and do not effect terrain roughness.) The wave number spectrum is presented in Figure 20.

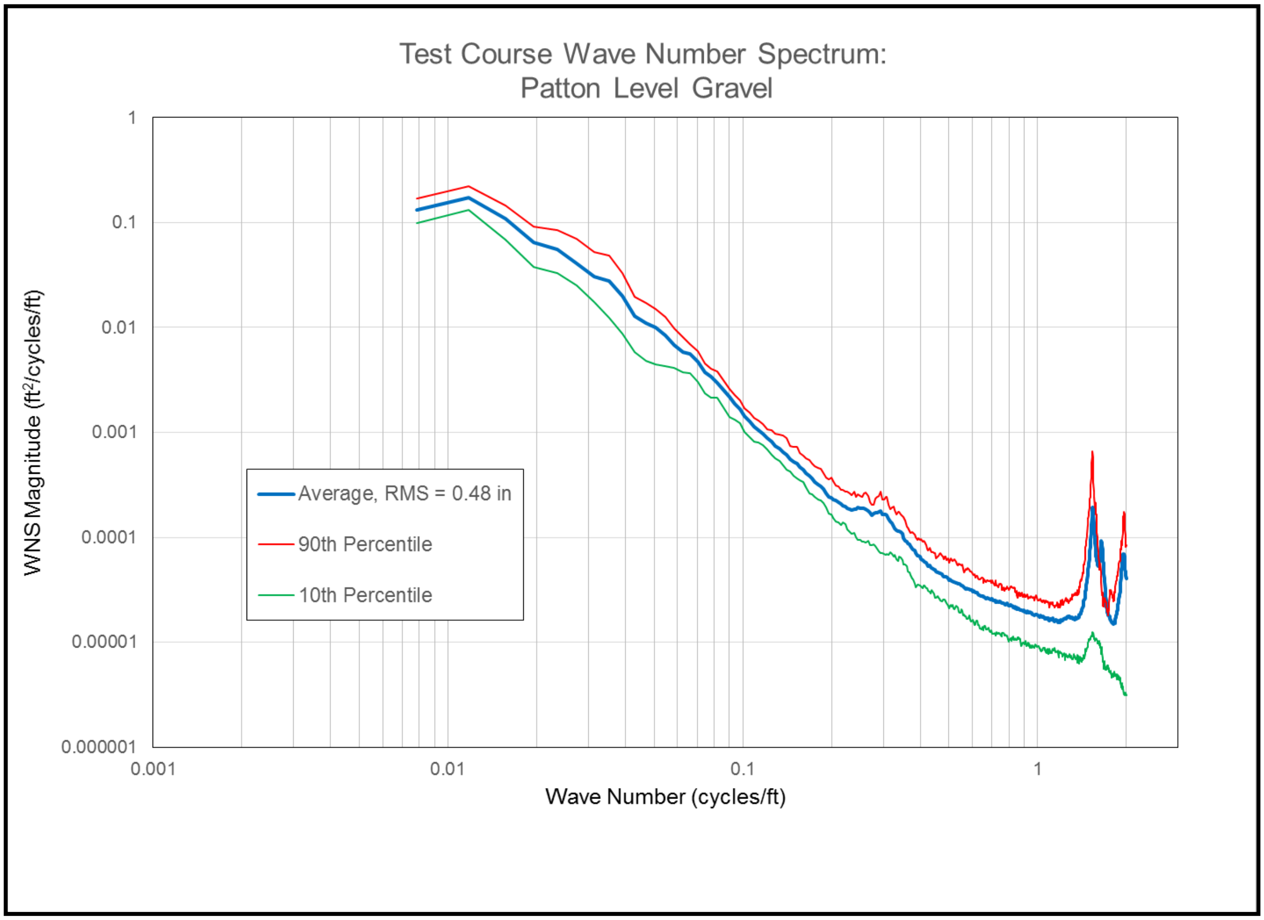

Figure 20. Patton Level Gravel Course WNS.

5.2.6 Patton Hilly Gravel (PHG).

The Patton Hilly Gravel course is an 8.0 km (5.0 mi) course containing many steep slopes. Course surfaces vary from sand and gravel to exposed bedrock. The two prominent landforms that the Patton Hilly Gravel course crosses are alluvial wash and fan, and other less common landforms consisting of bedrock, dissected fan, and alluvial terrace. The surface cover of the upper 5 cm (2 in.) of all these landforms are mostly subrounded to angular gravel that range from poorly-graded gravel with either silt, sand or clay to well-graded gravel with sand (Unified Soil Classification System (USCS): poorly graded gravel (GP), poorly graded gravel - silty gravel (GP-GM), and clayey gravel to well graded gravel (GC to GW)). The two dominant landforms exhibit Cristobol-Gunsight soil found on the Qf2 alluvial fan surface and Carrizo soil developed in alluvial washes. The wave number spectrum is presented in Figure 21.

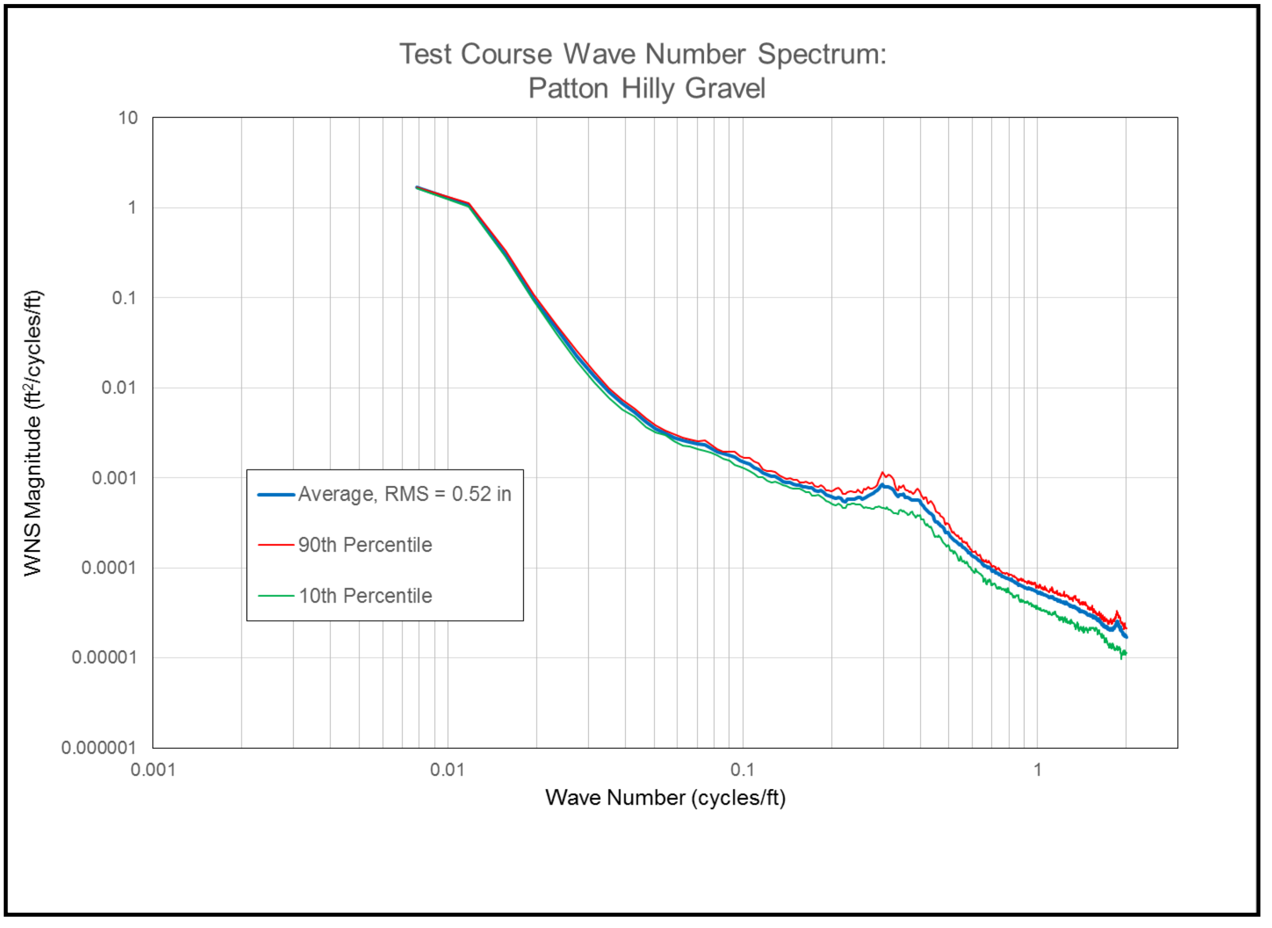

Figure 21. Patton Hilly Gravel Course WNS.

5.2.7 Patton Level Trails (PLT).

The Patton Level Trails is a 10.5 km (6.5 mi) loop that traverses level sandy terrain with many bumps to provide a severe test of vehicle suspensions with moderate loads on the drive train. The three prominent landforms that the Patton Level Trails course crosses are alluvial fans, alluvial plains, and washes. The surface cover of the upper 5 cm (2 in.) of these landforms are mostly subrounded to angular gravel that range from poorly-graded gravel with either silt, sand or clay to well-graded gravel with silt (USCS: GP, GP-GM, clayey gravel to silty sand (GC to SM), poorly graded sand - silty sand (SP-SM), and SP). These landforms exhibit three different soil types, which include Cristobol-Gunsight found on the alluvial fan surface, Superstition-Rositas developed on alluvial plains, and Riverbend developed on alluvial terraces and washes. The wave number spectrum is presented in Figure 22.

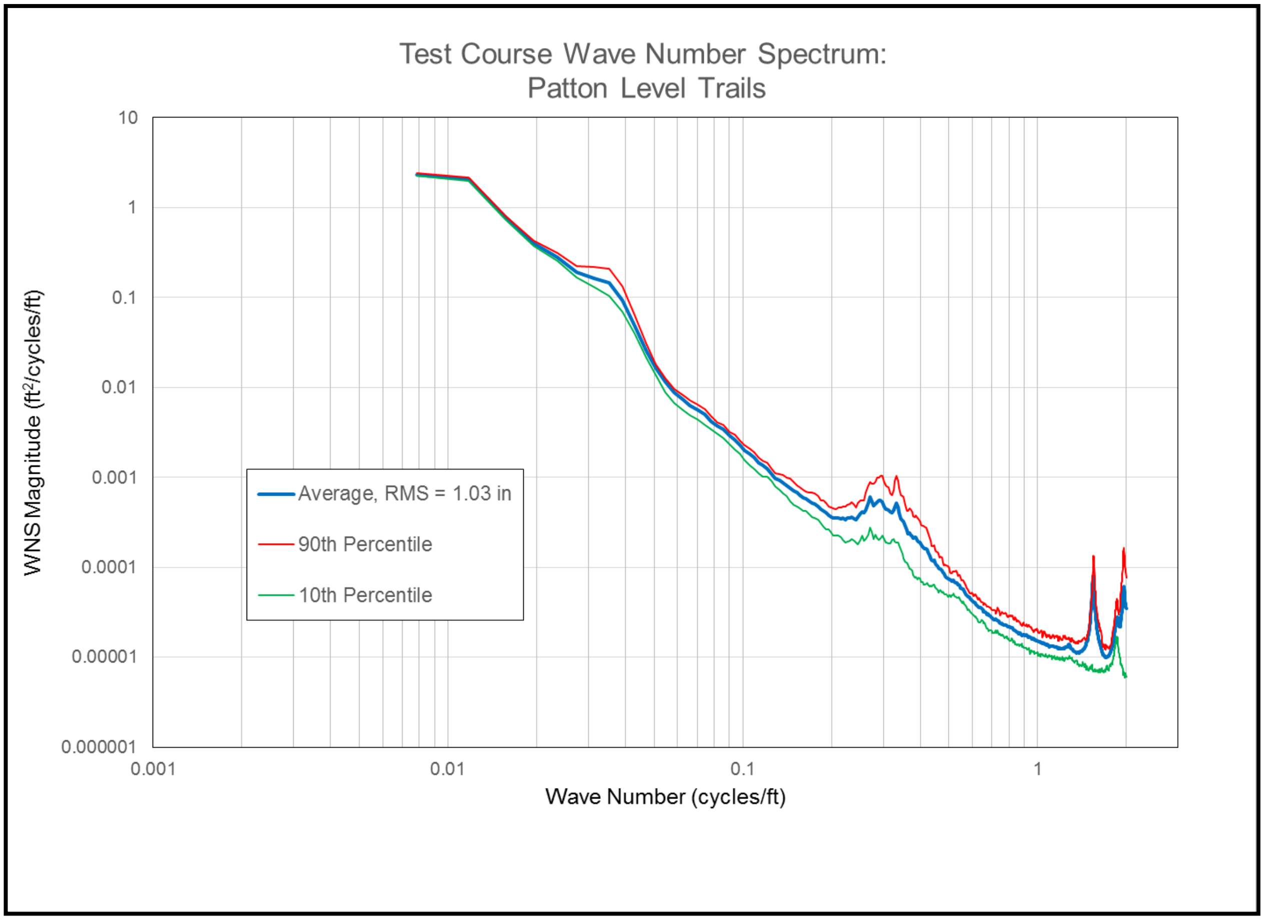

Figure 22. Patton Level Trails Course WNS.

5.2.8 Patton Hilly Trails (PHT).

Patton Hilly Trails is a 4.0 km (2.5 mi) loop course that crosses surfaces composed of sand, gravel, and exposed rock. This course contains many steep slopes. The three prominent landforms that the Patton Hilly Trails course crosses are bedrock, dissected fan, and alluvial fan. The surface cover of the upper 5 cm (2 in.) of these landforms are mostly subrounded to angular gravel that range from poorly-graded gravel with either silt, sand or clay to well-graded gravel with silt (USCS: GP, GP-GM, GC to GW-GM). These landforms also exhibit three different soil types, which include Lithic Torriorthents developed on bedrock, Gunsight-Chuckawalla developed on dissected fan surfaces, and Cristobol-Gunsight found on the alluvial fan surface. The wave number spectrum is presented in Figure 23.

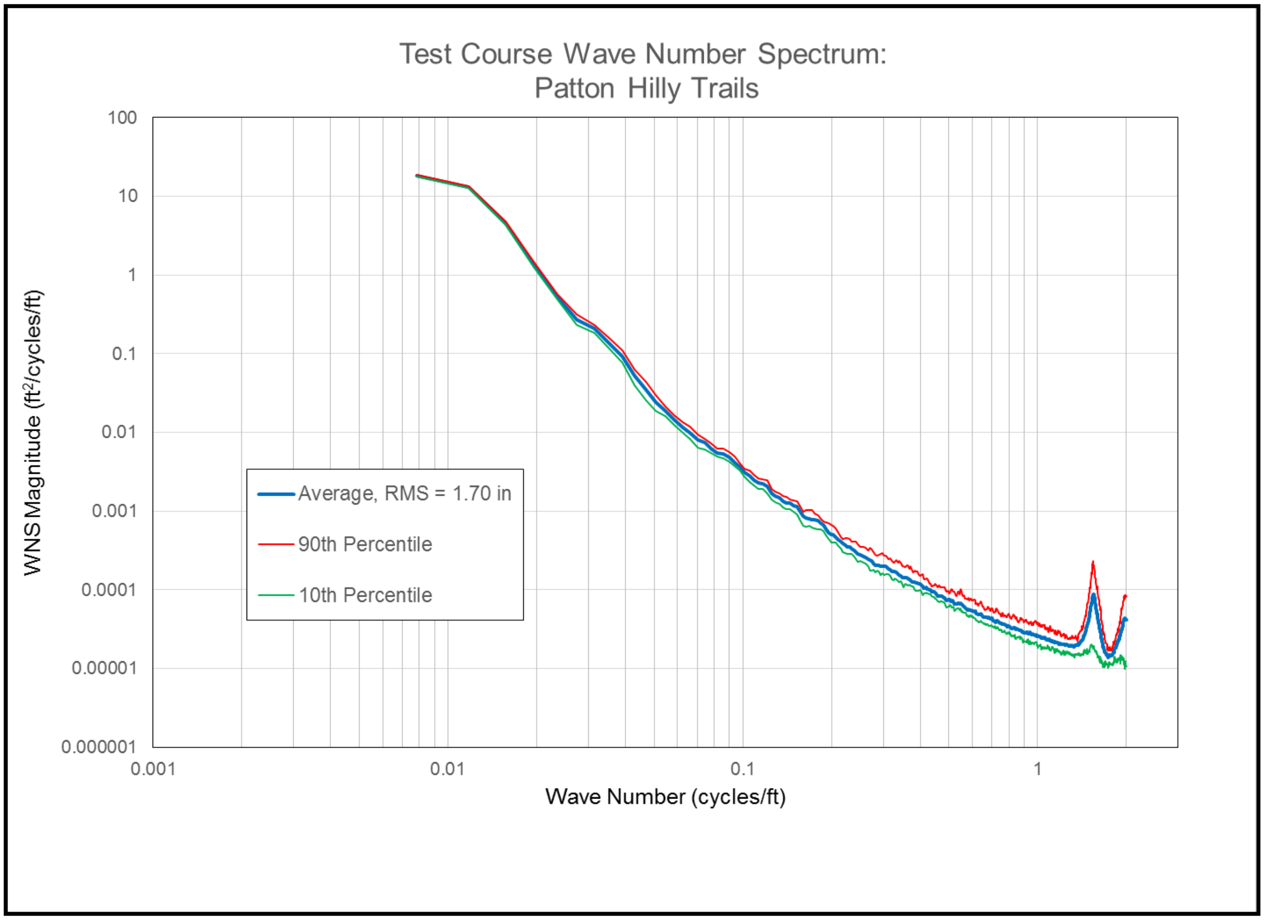

Figure 23. Patton Hilly Trails Course WNS.

5.2.9 Laguna Level Trails East and Laguna Level Trails West (LLTE and LLTW).

The Laguna Level Trails East endurance course consists of a 4.3 km (2.7 mi) loop course, whereas the Laguna Level Trails West is 9.0 km (5.6 mi) in length. Both loops cross surfaces composed mostly of sand and gravel. The Laguna Level Trails East has a slightly rough, relatively hard sand and gravel surface, and is suitable for tractor-trailer combinations and commercial trucks. The Laguna Level Trails West has more gravel and sand washes than the East Loop, and is suitable for commercial trucks. Both courses are nearly level except for gentle embankments where alluvial washes are crossed. The four landforms that the Laguna Level Trails East/West courses cross are dissected fan, alluvial fan, alluvial terrace, and wash. The surface cover of the upper 5 cm (2 in.) of these landforms are mostly subrounded to angular gravel that range from poorly-graded gravel with either silt, sand or clay to well-graded gravel with sand (USCS: GP, GP-GM, GC to GW). These landforms also exhibit four different soil types, which include Carsitas-Chuckawalla developed on dissected fan surfaces, Gunsight-Chuckawalla found on alluvial fan/terrace surfaces, Riverbend developed on terraces, and Carrizo formed within alluvial washes. The wave number spectra are presented in Figures 24 and 25.

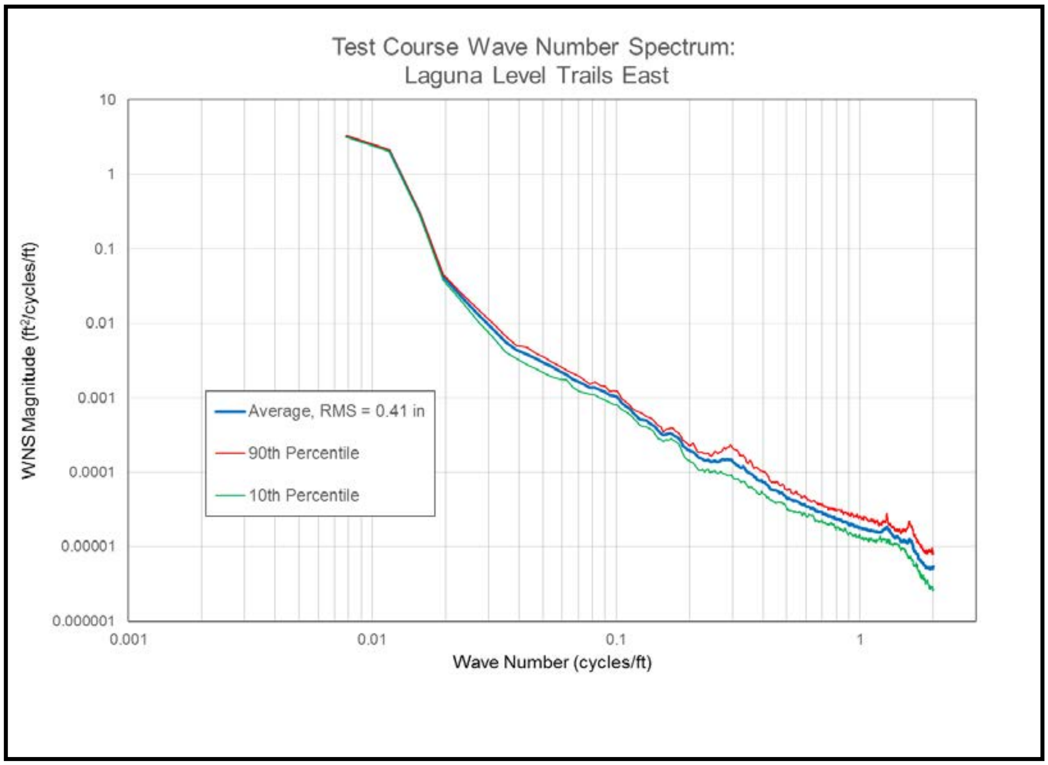

Figure 24. Laguna Level Trails Course - East Loop WNS.

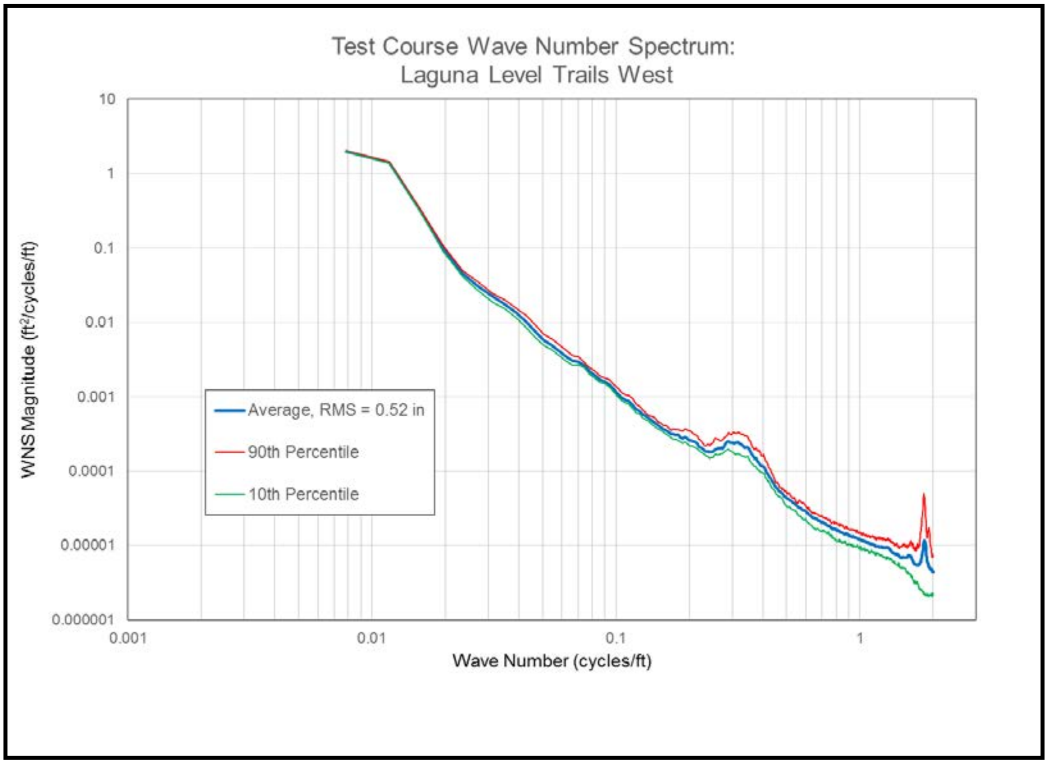

Figure 25. Laguna Level Trails Course - West Loop WNS.

5.2.10 Laguna Hilly Trails and Laguna Hilly Trails Short Course (LHT and LHTSC).

The Laguna Hilly Trails course is a 3.2 km (2.0 mi) loop course that traverses hilly terrain composed of loose rock, gravel, and sand. The Laguna Hilly Trails Short Course follows Laguna Hilly Trails except for bypasses around the steeper grades, and is intended for systems with minimal grades requirements. The four landforms that the Laguna Hilly Trails course crosses are bedrock, dissected fan, alluvial terrace, and alluvial wash. The surface cover of the upper 5 cm (2 in.) of these landforms are mostly subrounded to angular gravel that range from poorly-graded gravel with either silt, sand or clay to well-graded gravel with sand (USCS: GP, GP-GM, GC to GW). These landforms also exhibit four different soil types, which include Lithic Torriorthents found on bedrock, Gunsight-Chuckawalla developed on dissected fan surfaces, Cristobol-Gunsight on alluvial terraces, and Carrizo found within washes. The wave number spectra are presented in Figures 26 and 27.

Figure 26. Laguna Hilly Trails WNS.

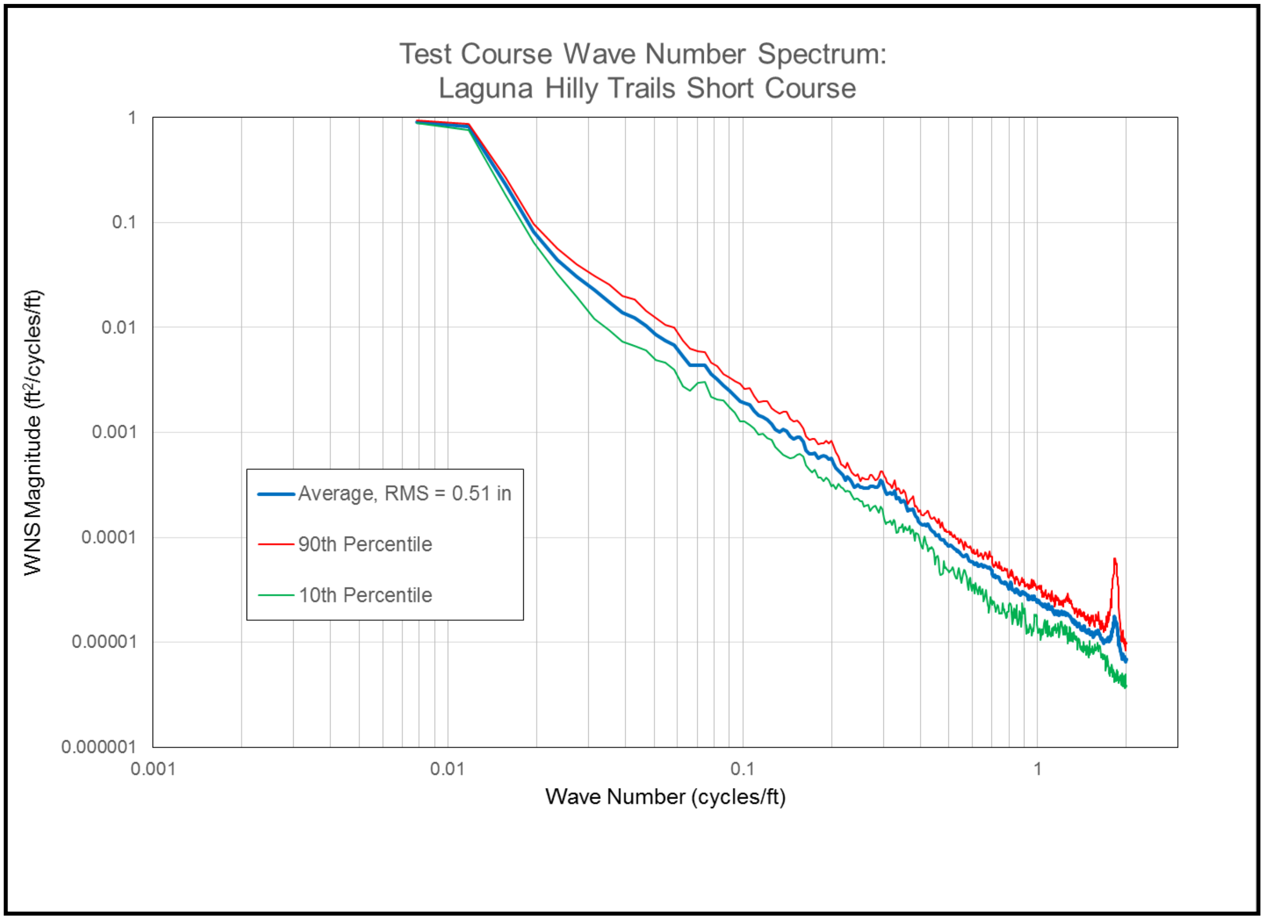

Figure 27. Laguna Hilly Trails Short Course WNS.

5.2.11 Middle East (ME).

This composite course is 33.1 km (20.6 mi) in length and replicates the terrains found in Middle Eastern countries. The most common soil complex is the Riverbend Family-Carrizo Family Complex composed of cobbly coarse loamy sands found in the wash bottoms. The second most common soil complex is the Gunfight Family-Chuckawalla Family Complex soils composed of gravely-loamy soils found on the terrace side slopes. The third most common soil complex is the Chuckawalla Family Gunfight Family Complex composed of fine very gravely loamy sands found on the top of terraces. The last soil complex encountered is the Gilman Family-Harqua Family -Glenbar Family Complex composed of very fine loamy silty soils found on the basin floors of the course. The wave number spectra is presented in Figure 28.

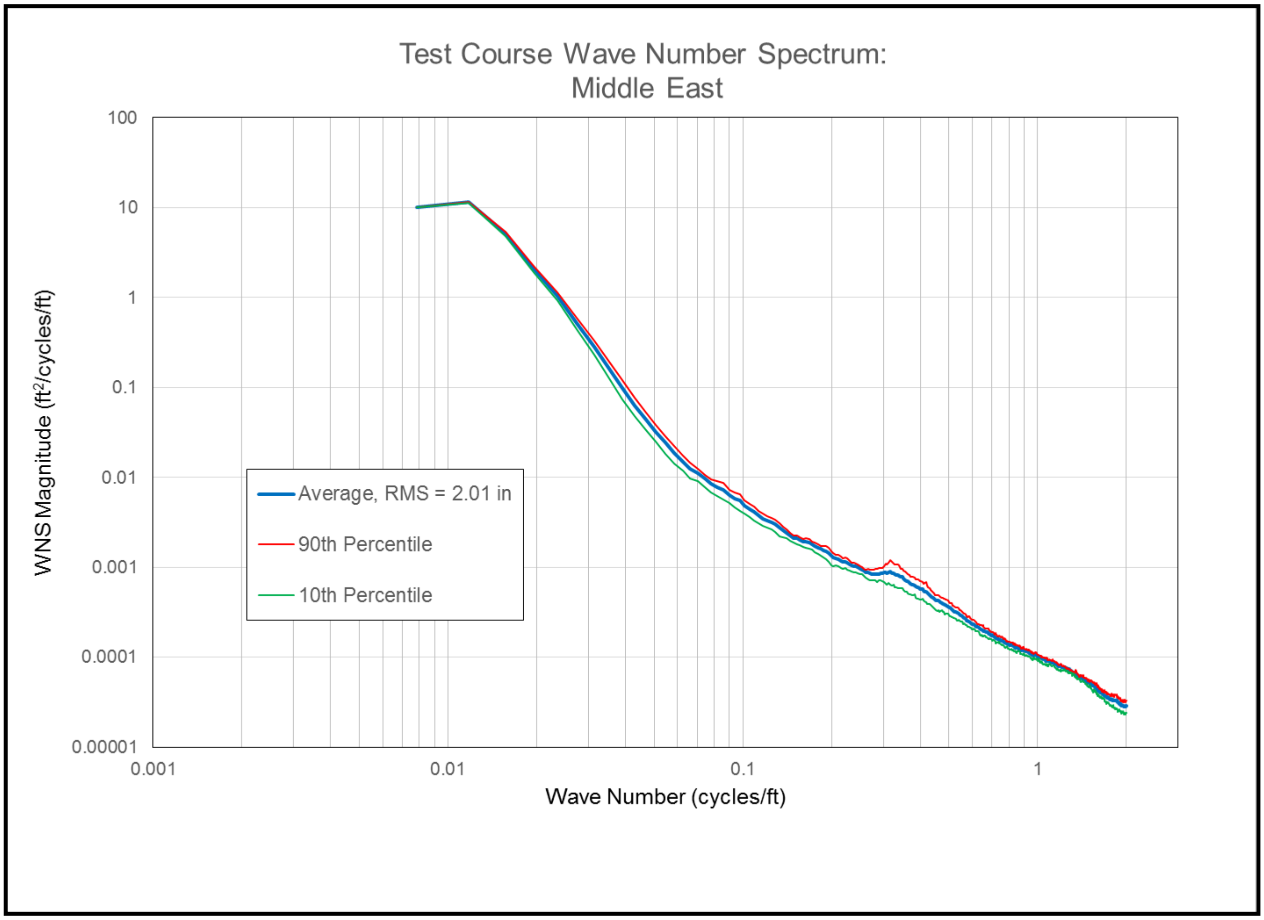

Figure 28. Middle East Course WNS.

5.2.12 Desert March (DM).

The Desert March course is a 40.7 km (25.3 mi) course through a variety of desert terrain features including limey fans, limey fan sandy, sandy uplands, sandy bottoms, and gravely hills. The route generally alternates between stretches of hard-packed alluvial fans that are broken up by washes or hills. This type of varying desert terrain despite having a relatively low average gradient, exposes a test vehicle to a rigorous test condition which exercises the suspension, brakes, and powertrain, as well as exposing the vehicle system to clearance issues caused by large dips. The wave number spectrum is presented in Figure 29.

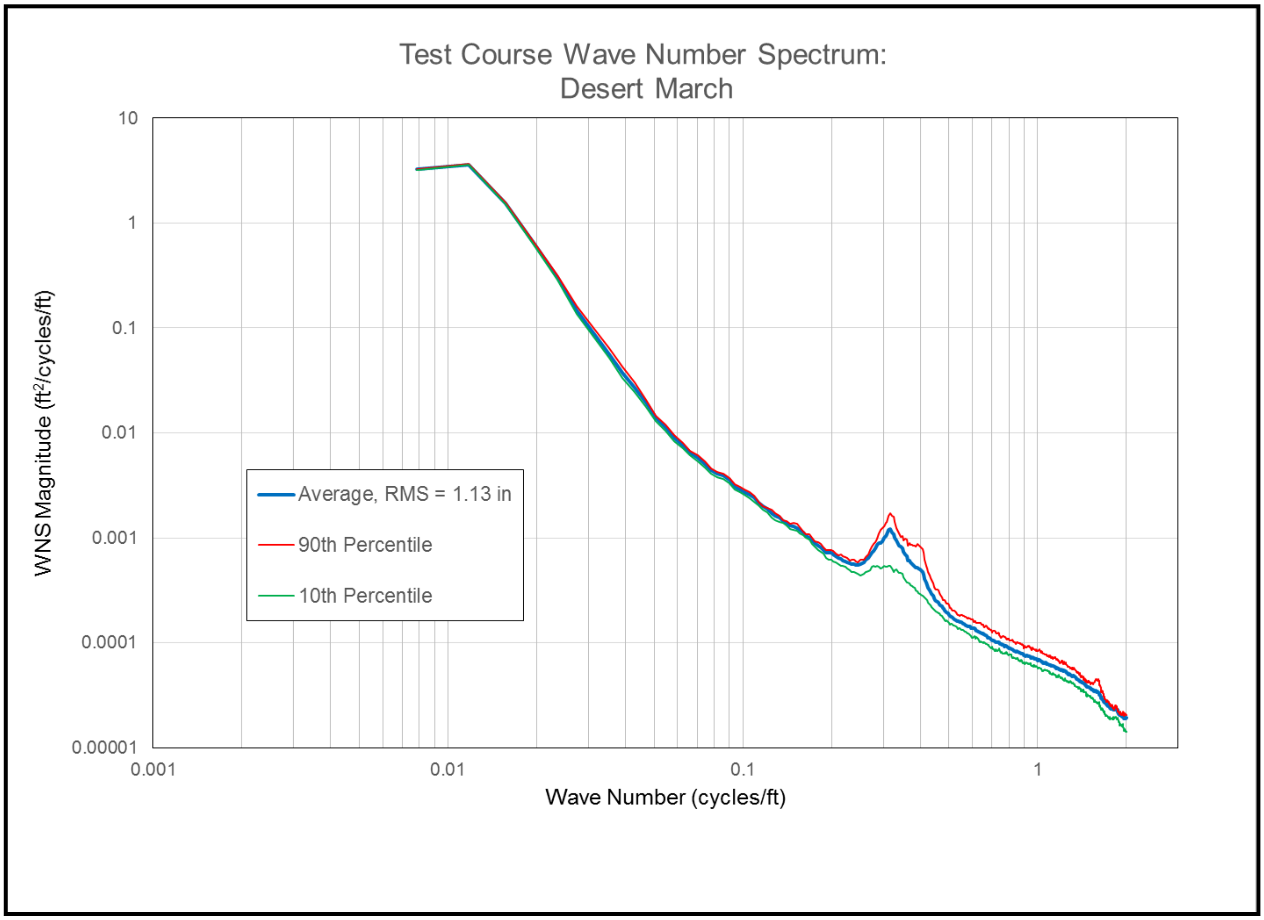

Figure 29. Desert March Course WNS.

5.2.13 Rock Ledge (RL).

This course is 6.3 km (3.9 mi) long, is located between two vertical rock outcroppings, and is traversed with several exposed rock ledges. The course follows a natural water course through the mini canyon. The terrain is classified as basalt hills, and volcanic hills. The surface of the trail is primarily composed of Riverbend Family-Carrizo Family Complex soils which are very coarse sands and very heavily cobbled. The second soil class is the Lithic Torriorthents and Typic Torriorthents complex. These soils are composed of fragmented bedrock, vertical rock outcrops, and very thin soil layers. They are usually strewn with large stones up to 76 cm (30 in.) in diameter that have spalled off the vertical ledges. In many cases there are no soils, just rocks of various sizes. The wave number spectrum is presented in Figure 30.

Figure 30. Rock Ledge Course WNS.

5.2.14 Overlay of YTC Test Courses.

The wave number spectra for the YTC courses described in this section are combined in Figure 31.

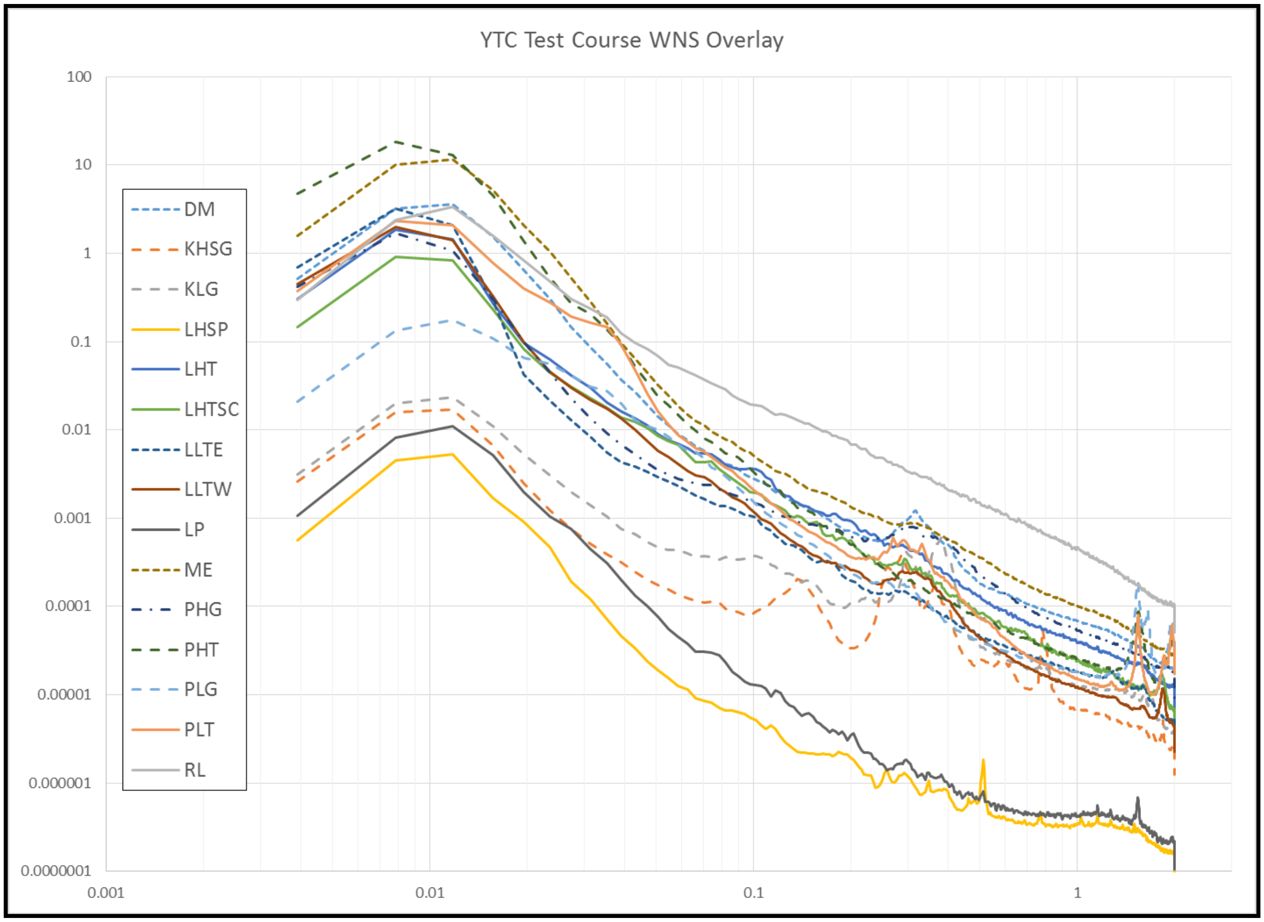

Figure 31. Overlay of YTC Endurance Test Courses.

5.3 Tropic Regions Test Center (TRTC) - Horoko Test Courses.

5.3.1 Summary.

a. Tropic Regions Test Center (TRTC) - Horoko Test Site (TRTC-Horoko) is located near Horoko, Panama, several miles to the west of Panama City. The courses are located in a tropical environment that experiences high rainfall, especially during the rainy season of May through November. The terrain at Horoko Test Site is relatively hilly and crossed by several washes that run following heavy rains.

b. The paved courses vary from smooth to extremely degraded, with the roughness of these areas being reflected in the terrain classification. The off-road courses traverse through the native jungle, where the plasticity of the soil results in relatively low short-wavelength roughness, but very high difficulty of maintaining traction following rains.

c. The soil of the off-road courses was collected at several locations and analyzed to determine composition. The soils were of fairly uniform composition: all soils had small particle size and high plasticity, with USCS classifications of primarily clay of high plasticity (CH) and some silt of high plasticity (MH). The particle size of the upper soil layers tended toward approximately 70-95% fines, 5-20% sands, and less than 10% gravels; deeper ruts had slightly increased particle sizes, tending toward 60-90% fines, 10-30% sands, and less than 10% gravels. Soils had an Atterberg plastic limit of around 20-30% water content, and a liquid limit usually between 50-60%. Finally, the cone penetrometer test was performed in order to obtain cone index data: in conditions where the water content was within the plastic limit, the cone index in the critical layer generally ranged from 50-100 psi except for location in stream beds, where the index was 100-150 psi when not hitting bedrock; when the soil was within the liquid limit following heavy rains, the cone index was reduced and could be as low as 0-50 psi in the critical layer.

d. Courses at TRTC-Horoko were profiled using a total station with rod-and-level in order to provide a general idea as to course terrain severity. Note that the courses were only profiled once, along a single path, and using one-foot intervals (rather than the standard 1/4-foot intervals). Another consideration with regards to TRTC profiles: most of the unimproved cross-country courses at TRTC undergo significant erosional changes during the course of testing due to the soft soil stability (as expected in tropics conditions under repeated traffic), so short- to medium-wavelength roughness measures for those courses should be expected to vary considerably over time.

e. The statistics for the Horoko test courses were calculated similarly to those at YTC and are presented in Tables 8 and 9 (IRI was not calculated primarily due to its need for a finer resolution than was used with the rod-and-level technique).

TABLE 8. TRTC-HOROKO COURSE RMS STATISTICS

COURSE NAME	RMS (in.)	1,024-FT SECTION RMS (in.)		
	Average	Min	Max	Std. Dev.
Course A	0.89	0.56	1.35	0.17
Course C	1.15	0.66	1.74	0.33
Course D	1.84	0.92	2.72	0.56
Kidney	1.21	0.87	1.42	0.14
Banana Spider	3.41	1.62	4.09	0.94
Bushmaster	1.88	1.49	2.48	0.26
Nickopedia	2.10	1.42	2.81	0.42

TABLE 9. TRTC-HOROKO COURSE GRADE STATISTICS

COURSE NAME	GRADE (%)	
	Max	Std. Dev.
Course A	7.5	3.2
Course C	9.8	3.8
Course D	15.3	7.0
Kidney	14.0	8.0
Banana Spider	12.6	5.2
Bushmaster	18.4	5.9
Nickopedia	14.5	4.8

5.3.2 Course A.

Course A is a 3.74 km (2.34 mi) long paved road. Course A ranges from smooth to heavily degraded, and is generally classified as 44% primary, 10% secondary, and 46% trails. The wave number spectrum is presented in Figure 32.

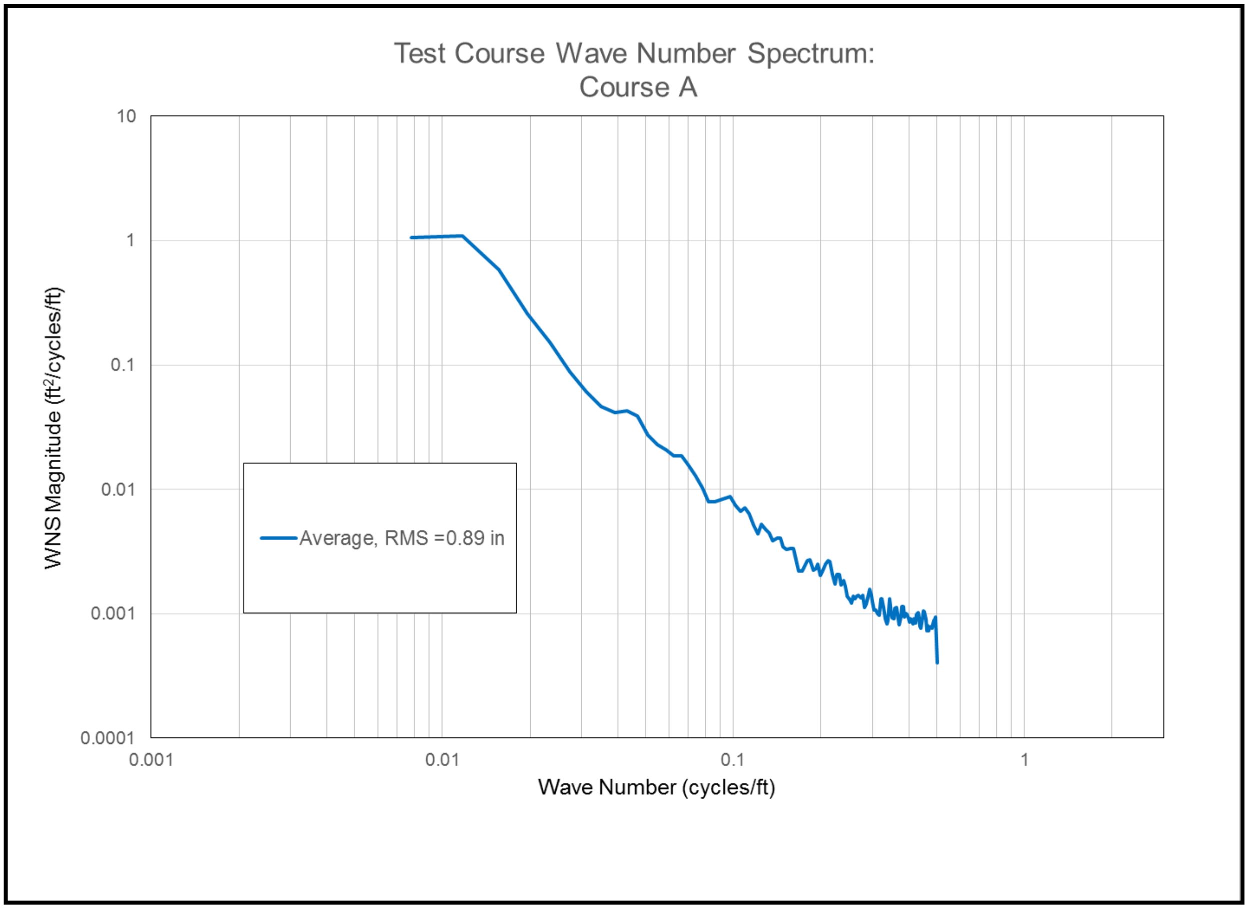

Figure 32. Course A WNS.

5.3.3 Course C.

Course C is a 1.42 km (0.89 mi) long gravel secondary road. The wave number spectrum is presented in Figure 33.

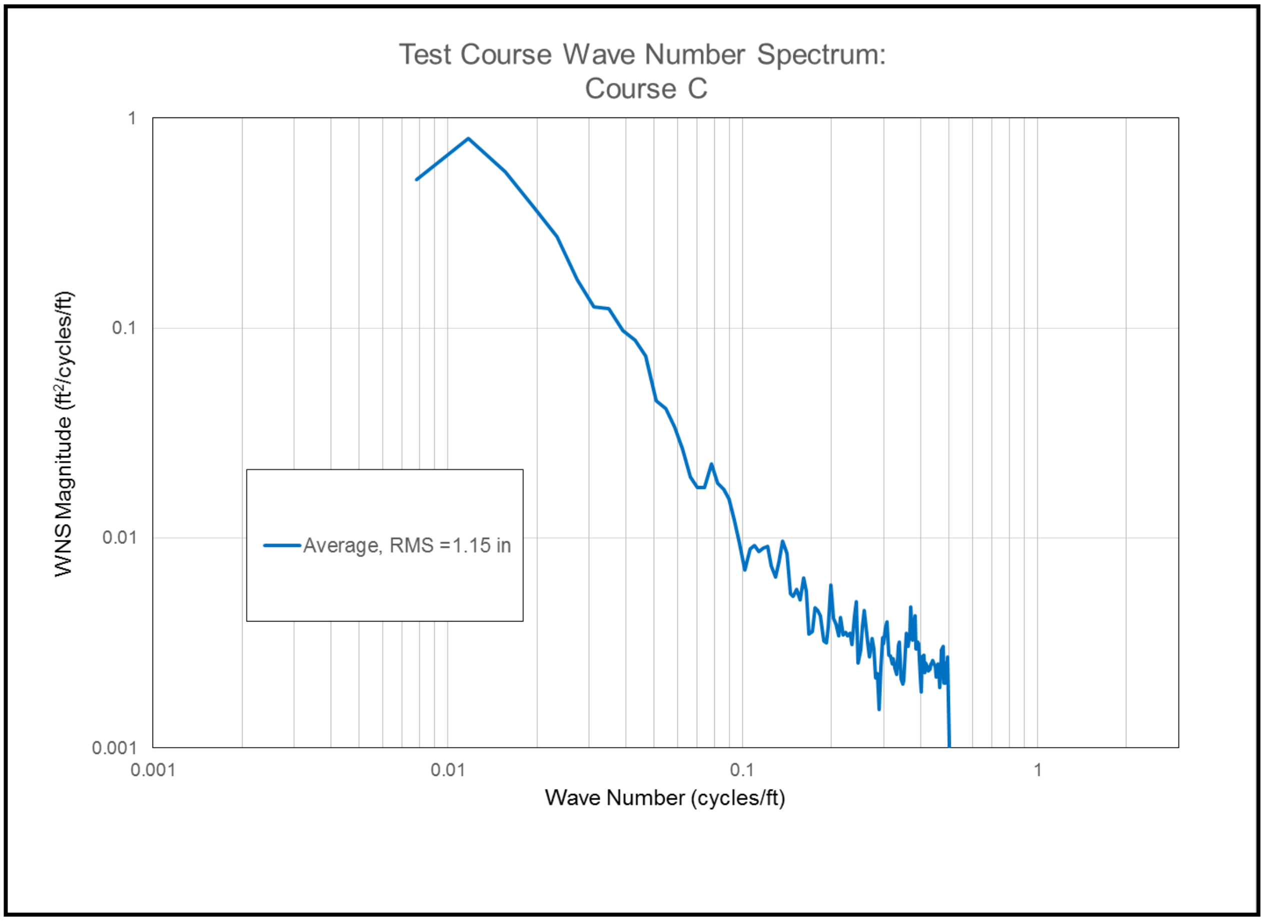

Figure 33. Course C WNS.

5.3.4 Course D.

Course D is a 1.00 km (1.60 mi) long degraded paved road that has numerous short hills and undulations. The wave number spectrum is presented in Figure 34.

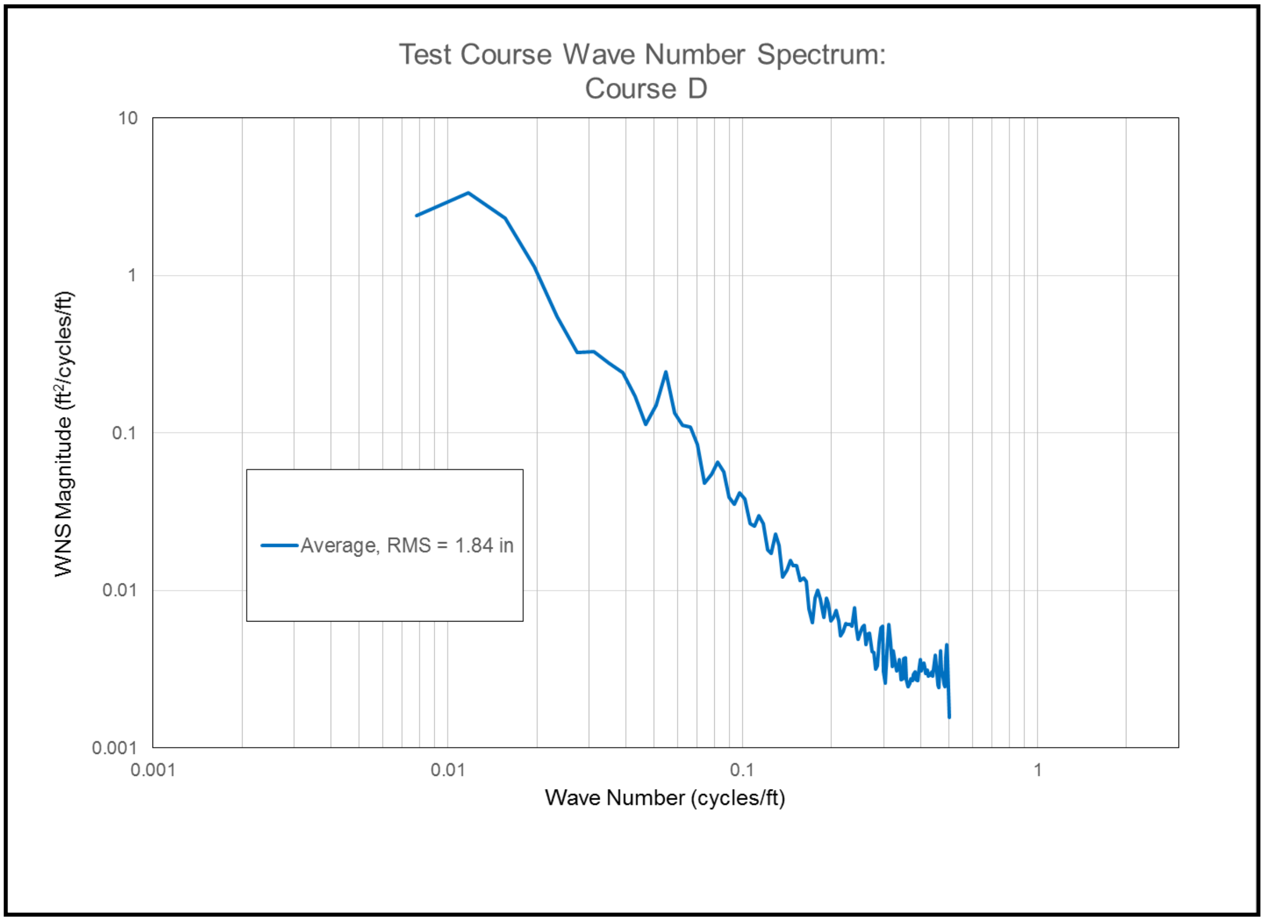

Figure 34. Course D WNS.

5.3.5 Kidney.

Kidney is a 0.56 km (0.35 mi) long paved road that is extremely degraded, resulting in extensive short-wavelength roughness. The wave number spectrum is presented in Figure 35.

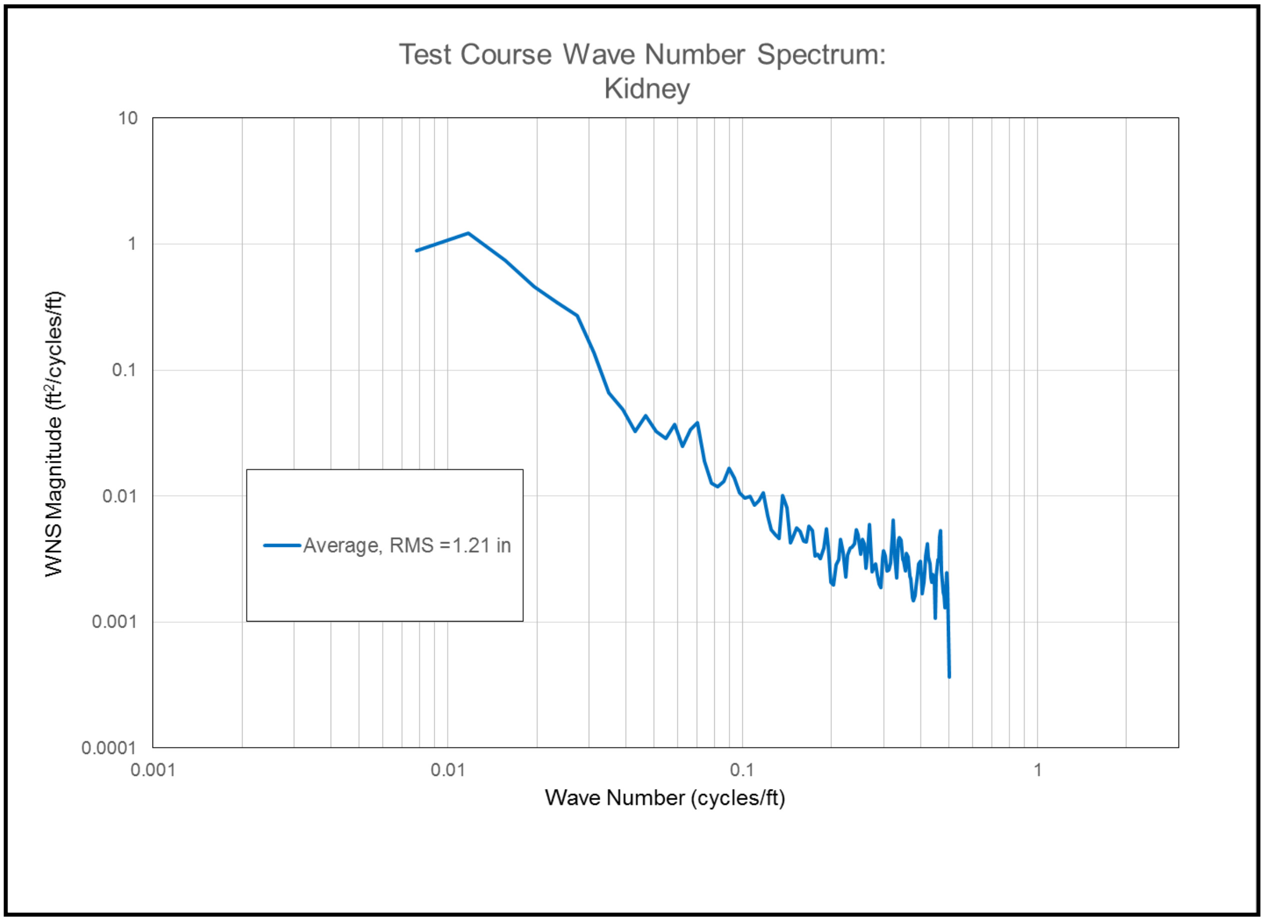

Figure 35. Kidney Course WNS.

5.3.6 Banana Spider.

Banana Spider is a 0.40 km (0.25 mi) long cross-country course. The soil on Banana Spider has not been improved, resulting in extreme traction challenges following rains. The wave number spectrum is presented in Figure 36.

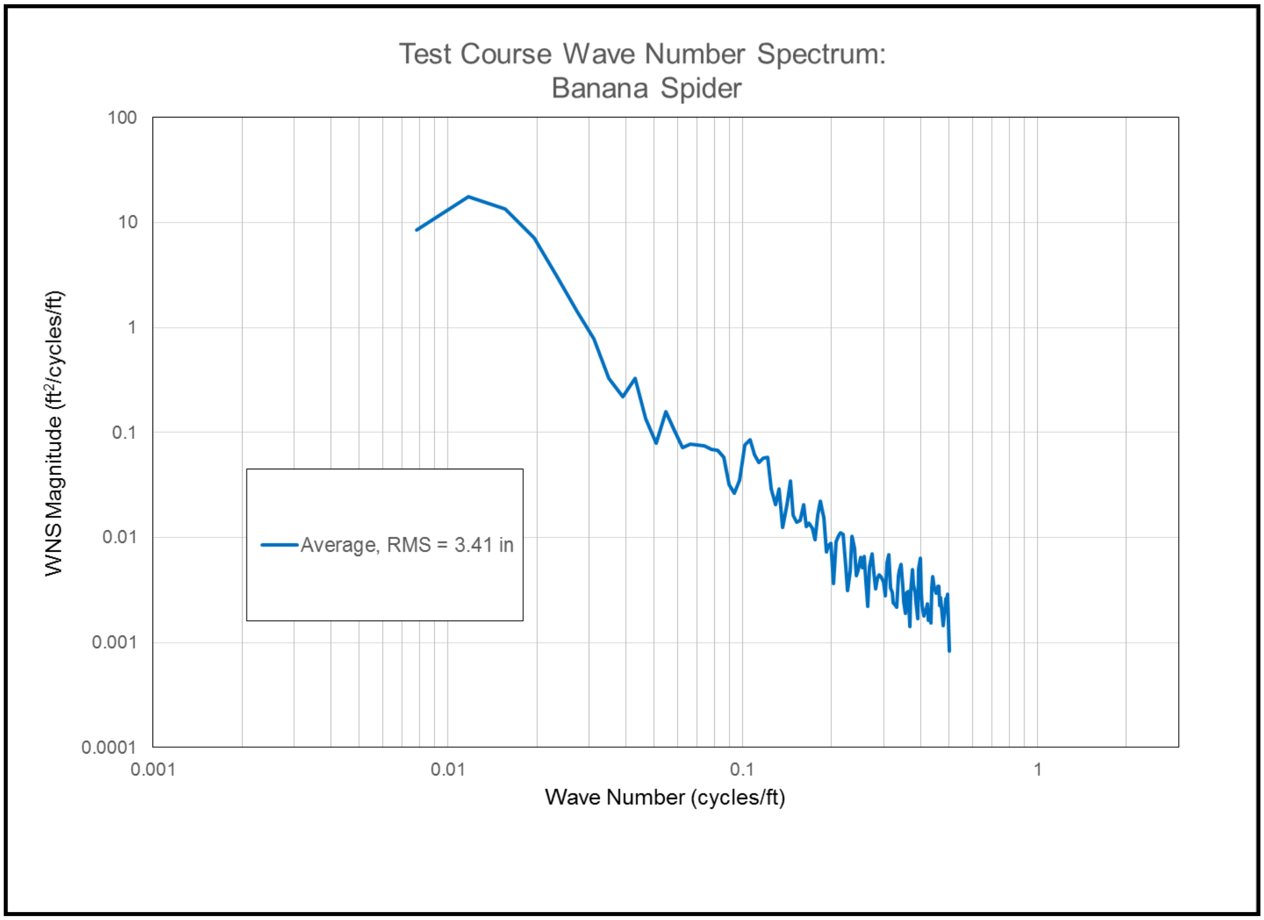

Figure 36. Banana Spider Course WNS.

5.3.7 Bushmaster.

Bushmaster is a 0.82 km (0.51 mi) long cross-country course. Bushmaster has been modified from the natural terrain by the addition of course material (known locally as tosca) to improve traction, and by the addition of several logs buried in sections of the course that must be traversed; the logs are buried approximately to the midpoint of their diameters, range from approximately half a foot to one foot high, and extend laterally over only one or the other side of the course (so only one side of the vehicle maneuvers over any log). The wave number spectrum is presented in Figure 37.

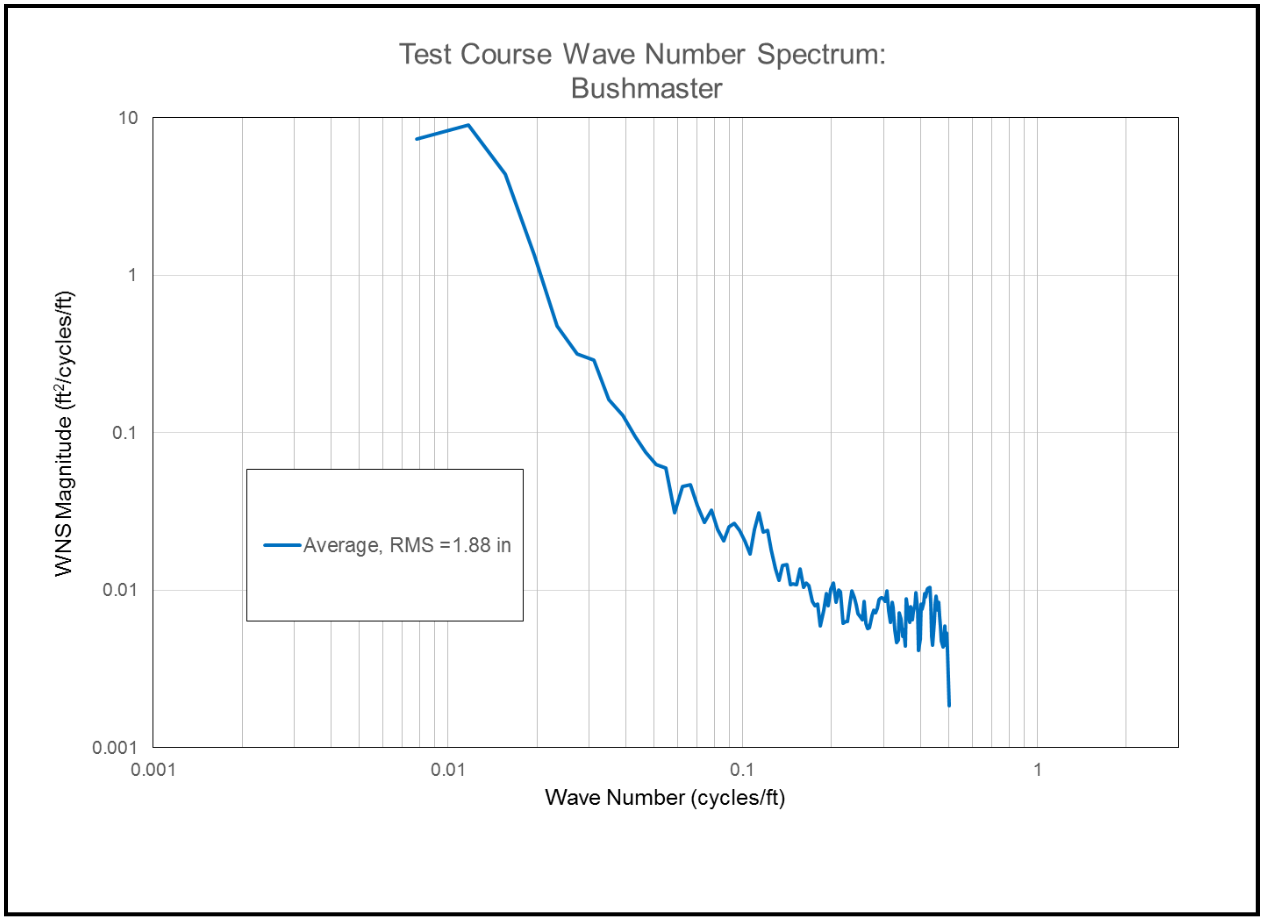

Figure 37. Bushmaster Course WNS.

5.3.8 Nickopedia.

Nickopedia is a 1.39 km (0.87 mi) long cross-country course. The soil on Nickopedia has not been improved, resulting in extreme traction challenges following rains. A short section of the course traverses a usually dry stream bed with large embedded rocks (the course is not run during heavy rains). The wave number spectrum is presented in Figure 38.

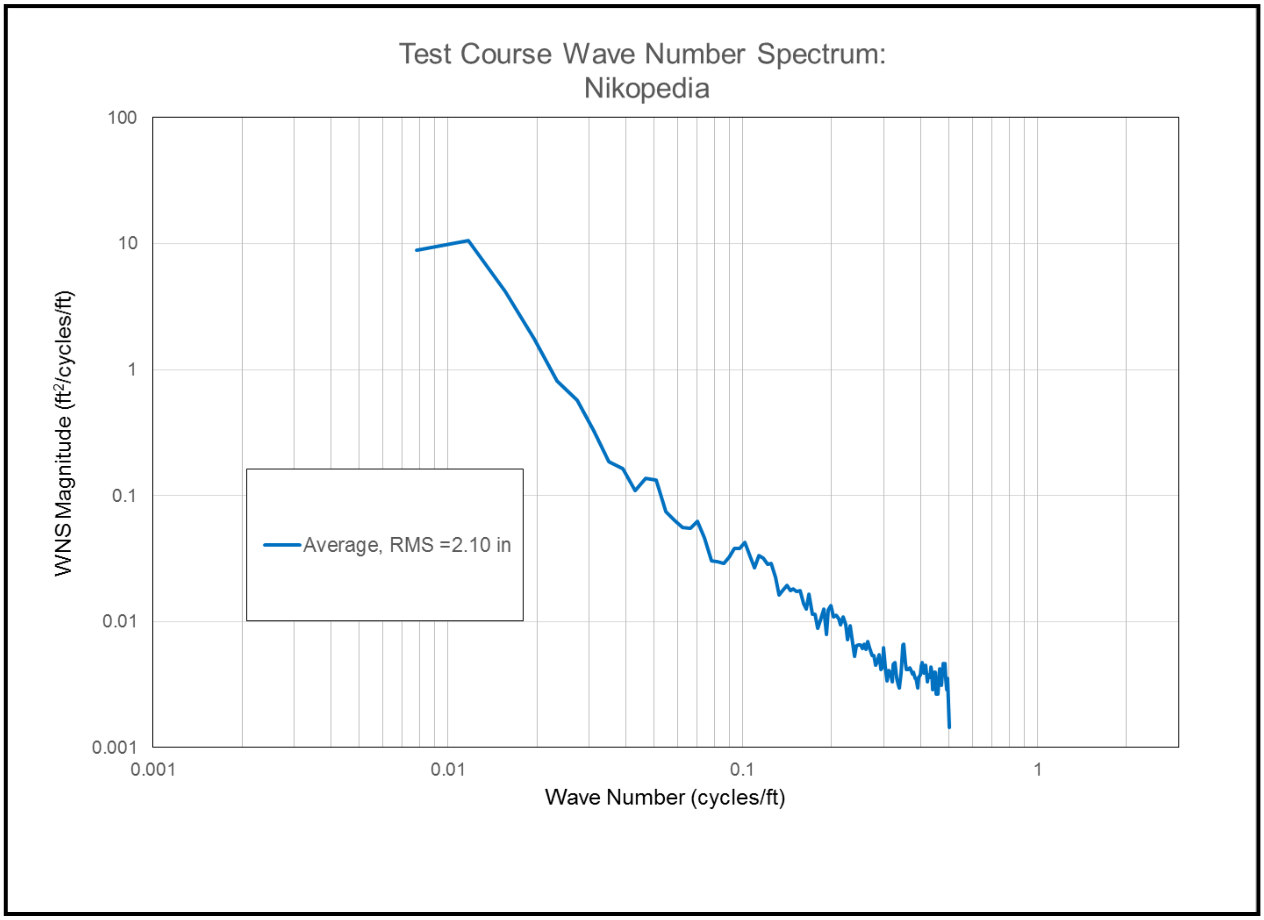

Figure 38. Nickopedia Course WNS.

6. SOIL CLASSIFICATION.

Soil classification descriptions are provided in Tables 10-12, which describe particle size classes, USCS classifications, and U.S. Department of Agriculture (USDA) classifications, respectively.

TABLE 10. PARTICLE SIZE CLASSES

CLASS	SIZE
Cobble and Gravel	>4.75 mm particle diameter (No. 4 sieve)
Sand (sand-sized)	<4.75 mm to >75 um particle diameters (No. 3 to No. 200 sieves)
Silt and Clay (silt and clay-sized)	<75 um particle diameters (No. 200 sieve)

TABLE 11. USCS CLASSIFICATION

USCS SYMBOL	DESCRIPTION
SW-SM	Well-graded sand with silt
SM-SP-SM, SP	Poorly-graded sand silt to poorly-graded sand to well-graded sand to well-graded sand
GW	Well-graded gravel with sand
GW-GM, GP-GM	Well-graded gravel with silt to poorly-graded gravel with silt
GC-GM, CL GP-GM	Silty, clayed gravel with sand to sandy clay to poorly-graded gravel with silt
GP-GM, GC	Poorly-graded gravel with silt to poorly-graded gravel with silt to clayey gravel
GM	Silty gravel with sand
GP, GP-GM, GC	Poorly-graded gravel with sand to poorly-graded gravel with silt to clayey gravel
CH	Clay of high plasticity, fat clay
MH	Silt of high plasticity, elastic silt

TABLE 12. USDA SOIL CLASSIFICATION

USDA SOIL CLASSIFICATION	DESCRIPTION
Superstition-Rositas	Sand
Carrizo	Extremely gravelly loamy coarse sand
Riverbend	Extremely cobbly sand loam
Cristobol-Gunsight	Silty, clayey gravel with sand to sandy day to poorly-graded gravel with silt
Gunsight-Chuckawalla	Extremely gravelly sandy loam to extremely gravelly loamy fine sand to very gravelly silt
Carsitas-Chuckawalla	Extremely gravelly sand to extremely gravelly loamy fine sand to very gravelly silt loam
Lithic Torriorthents	Extremely gravelly sandy loam

7. ROAD SURFACE CLASSIFICATION.

a. Test item specifications generally divide descriptions of road surfaces into categories used to describe the degree of improvement of the terrain. Most commonly, these four categories are presented as primary roads, secondary roads, trails, and cross country (many systems combine trails and cross-country into one category). Finer subcategory distinctions can be made between surface types, though difficulties will arise in identifying appropriate test courses if the specifications are too distinct. Specifications often consist of qualitative descriptions of a particular surface and a range of RMS roughness values associated with that surface. (Specifying a range of RMS values is important for multiple reasons; this includes recognizing that test courses will experience a reasonable variation in RMS values due to weather, wear and maintenance.)

b. The qualitative descriptions are generally consistent throughout the wide spectrum of test items, but the corresponding RMS roughness values vary somewhat amongst the test items. For a given test item, the RMS value ranges describing the terrain categories may overlap. The overlap is understandable given that many factors influence RMS (as described in Section 4), and many aspects are considered when describing terrain (RMS alone should not define a surface). For example, a hilly secondary road may have the same RMS as a level surface traditionally defined as cross country. The distinction between Trails and Cross-Country is particularly difficult, with those two categories commonly being grouped as “off-road”. The Belgian Block course could be considered a secondary road because it is constructed from cobblestones; however the surface roughness is severe enough that Belgian Block is used in many tests to represent off-road inputs.

c. The results of an endurance test are a function of many test course attributes such as longitudinal slope, side slope, mud/dust, soil strength, radius of curvature, and surface roughness. The response of a vehicle to surface roughness is dependent upon the shape of the wave number spectrum and the vehicle speed. Therefore, having equivalent RMS roughness values does not imply that two test courses will produce equivalent test results. The selection of test courses with which to evaluate test requirements should be performed with thoughtful consideration, not simply by matching RMS values.

d. Suggested qualitative descriptions and RMS roughness values are presented as follows:

(1) Primary Roads: All weather, maintained, hard surface (paved) roads with good driving visibility used for heavy and high density traffic. These roads have lanes with a minimum width of 2.7 m (9 ft), and the legal maximum gross vehicle weight/gross combination weight (GVW/GCW) for the country or state is assured for all bridges. These roads are surfaces having an RMS roughness value of less than 0.5 cm (0.2 in.) and an average IRI (50 mph) generally less than 200 inches per mile.

(2) Secondary Roads: All weather, occasionally maintained, hard or loose surface (e.g., large rock, paved crushed rock, gravel) intended for medium-weight, low-density traffic. These roads have lanes with a minimum width of 2.4 m (8 ft) and no guarantee that the legal

maximum GVW/GCW for the country or state is assured for all bridges. These roads are surfaces typically having an RMS roughness value varying between 0.3 and 1.8 cm (0.1 and 0.7 in.); the average IRI (25 mph) for secondary roads generally varies from 200 to 1000 inches per mile.

(3) Trails: One lane, unimproved, seldom maintained loose surface roads, intended for low density traffic with an expectation that characteristics will change as the weather changes from dry to wet. Trails have a minimum width of 2.4 m (8 ft), no large obstacles (boulders, logs, stumps) and no bridging. These are surfaces typically having an RMS roughness value varying between 1.0 and 3.8 cm (0.4 and 1.5 in.); the average IRI (25 mph) for trails varies from 400 to 2500 inches per mile.

(4) Cross-Country: Vehicle operations over terrain not subject to repeated traffic and where no roads, routes, well-worn trails or man-made improvements exist. (This definition does not apply to vehicle test courses which are used to simulate cross-country terrain). These are surfaces typically having an RMS roughness value from than 2.0 cm (0.8 in.) to 12.7 cm (5.0 in.), and an average IRI (15 mph) from 800 to over 6000 inches per mile.

APPENDIX A. ATC LASER PROFILER.

A.1. SYSTEM OVERVIEW.

a. The ATC Laser Profiler consists of a HMMWV with a rear mounted platform supporting a Class 3B laser scanner system coupled with a Novatel Inertial Navigation System (INS). The INS consists of a high grade Inertial Mass Unit (IMU), which produces triaxial accelerations and triaxial rotational measurements, and a differential Global Positioning System (GPS). A rear view of the system is presented in Figure A-1.

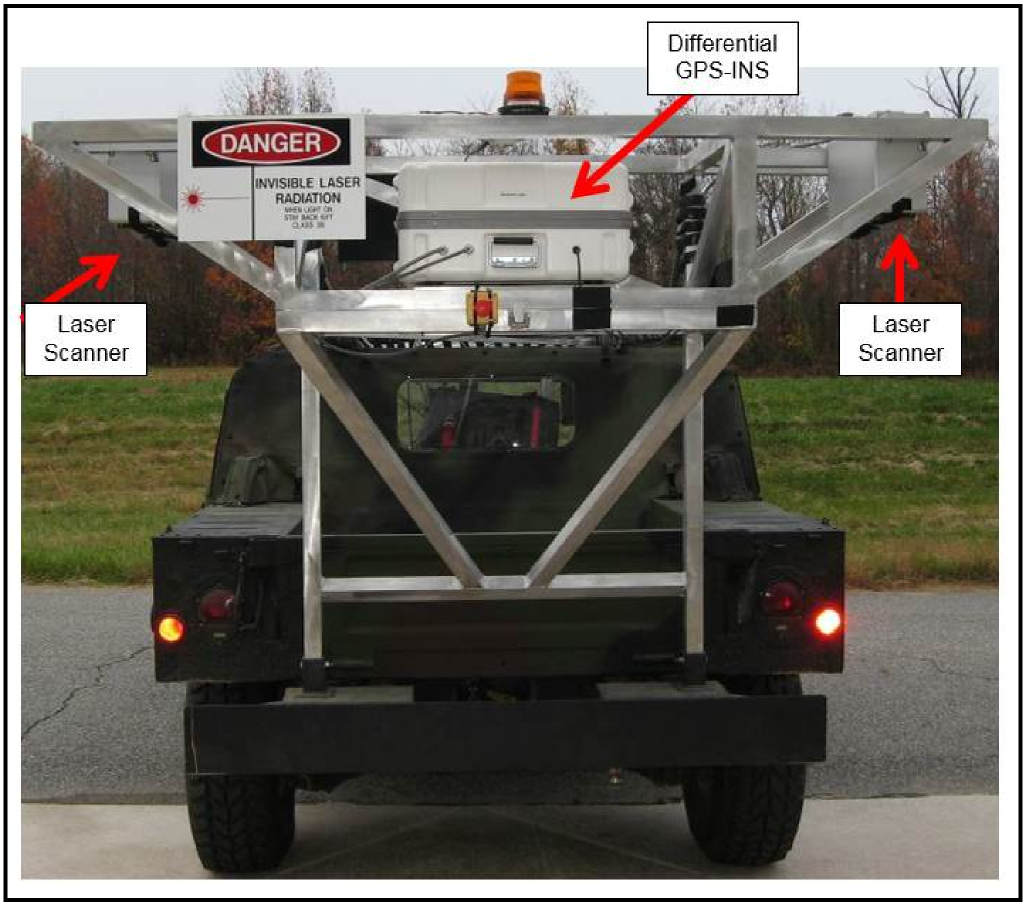

Figure A-1. Rear view of the ATC Laser Profiler.

b. The laser system projects lines perpendicular to the direction of travel, resulting in a scanned area that is about 12 ft wide. Unlike the previous cart based system, the ATC Laser Profiler data are sampled as a function of time, not forward distance traveled. The typical laser scanning rate is 1000 Hz, with about 4000 points from a single scan, resulting in a sample rate of about 4 MHz. The motion pack of the INS is sampled at 100 Hz, while the differential GPS data are sampled at 5 Hz. The starting and stopping of the scanner is controlled by a hand trigger. Typically an entire course is measured in one data run. The laser scan density is dependent upon

APPENDIX A. ATC LASER PROFILER.

the vehicle speed, which varies with each course. A rough estimate places typical sampling rates at about 1 billion data points per mile.

A.2. DATA PROCESS FLOW.

a. The data flow diagram for merging and processing the different sources of data is presented in Figure A-2. As mentioned previously, the GPS, IMU, and laser scanner are all sampled at different rates. The key to putting the INS and laser scans on the same time basis is having the laser scans triggered by a pulse clock emitted by the INS. The INS data are used to place the relative height data of the laser scanner into global coordinates. However before the laser data can converted into global coordinates, the precise position and orientation of the laser platform must be determined. This is performed by using several processing steps in the proprietary software Novatel Inertial Explorer (version 8.30.2105)**. The INS solution is then merged with the laser data using software developed by the Virginia Tech group which designed ATC's Laser Profiler. Data are then extracted from the resulting point cloud to suit various analytical needs. Most frequently, this involves extracting individual line (distance vs. elevation) profiles, which are then analyzed with traditional techniques.

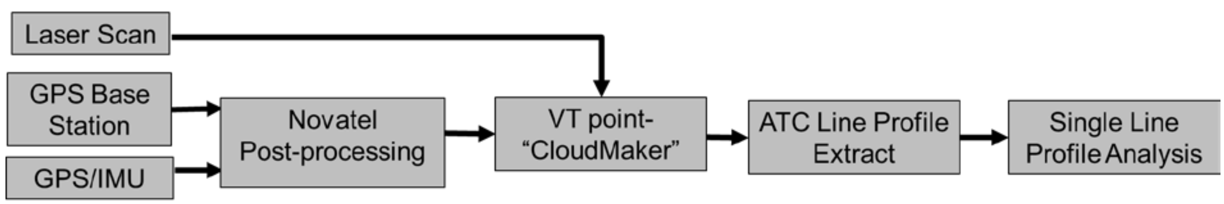

Figure A-2. Data process flow.

b. The Novatel post-processing occurs in several stages. Initially the differential GPS solution is determined by analyzing the raw message signals received by both the rover (the profiler HMMWV) and the fixed base station. The next stage employs a tightly-coupled Kalman filter to integrate IMU data with the differential GPS solution to yield an even more precise solution. Detailed information is used in this analysis, such as the vehicle platform type, the error model for the IMU model, as well as the location of the IMU relative to the rover GPS antenna. The last stage involves passing the tightly-coupled solution through a smoothing algorithm. Each stage employs a "forwards and backwards" analysis, which yields greater accuracy and is an advantage of processing after all data have been collected. The GPS/IMU data are then exported to be merged with the laser data. The final data set is a time history of the lateral, longitudinal, and altitude positions of the platform as well as precise pitch, roll, yaw, and other orientation signals.

** The use of brand names does not constitute endorsement by the Army or any other agency of the Federal Government, nor does it imply that it is best suited for its intended application.

APPENDIX A. ATC LASER PROFILER.

c. Because the INS and laser scanner are on the same platform, and sampled on the same time basis, the orientation and position of the laser scan data can be rectified to account for the motion of the platform. This rectification is performed in post processing using the Virginia Tech software “CloudMaker”. The result is a three coordinate (XYZ) point cloud of data, which represents the surface being scanned. The X, Y, and Z coordinates correspond to the GPS system Universal Transverse Mercator (UTM) Northings, Eastings, and height measurements, with the differential GPS base station having the (X,Y) position of (0,0). Sample renderings of the point clouds are presented in Figure A-3. The data can optionally be exported in three formats: full density laser scans of the entire width; full width scans down sampled by a factor of 100; or “wheelpath” data, which provides full density data but cropped to only nominally cover the paths of a HMMWV’s rear wheels. The wheelpath data files permit working with full density scans but with smaller file sizes.

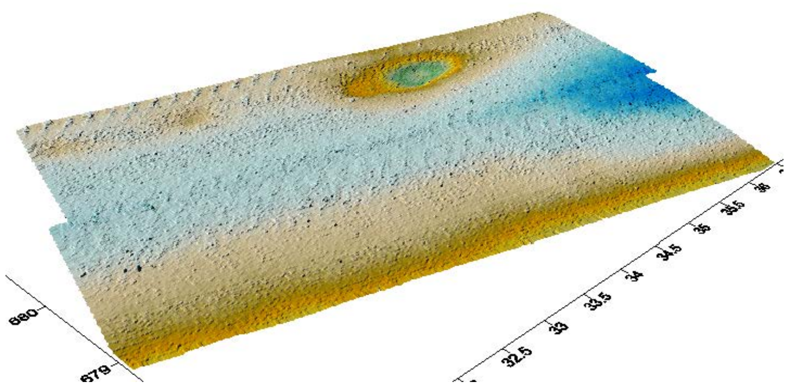

Figure A-3. Surface scan rendering from MTA Improved Gravel with pseudo-color indicating height. Note the pothole, the tread marks from individual tires, and the crowning in the course.

d. Many different techniques can be used to analyze the surface point cloud. The standard technique involves extracting from the cloud single line profiles of Distance vs. Height, with an evenly spaced sampling along each line (typically 0.25 ft). The current practice is to derive the horizontal plane (XY) coordinates of each profile line as parallel offsets to the XY coordinates of the final INS solution, after low pass filtering the INS solution to remove HMMWV body-roll effects. (The wheelpaths of the HMMWV are at approximately ± 3 ft offsets from the INS path.) Surface interpolation techniques are used to determine the elevation (Z) at the XY coordinates which define the single line profile. The distance along the profile is determined from those same XY coordinates. The extracted profile lines are then analyzed individually. An example plot of parallel profile lines falling within wheelpath point clouds is provided in Figure A-4. Examples of elevation profiles are provided in Figures A-5 and A-6.

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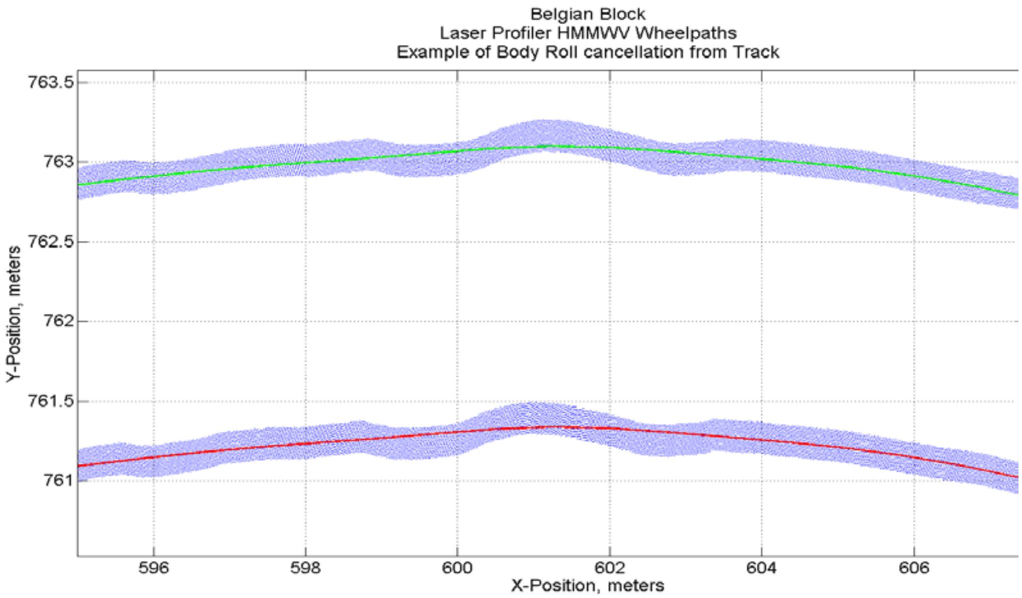

Figure A-4. Parallel profile lines falling with wheelpath point clouds.

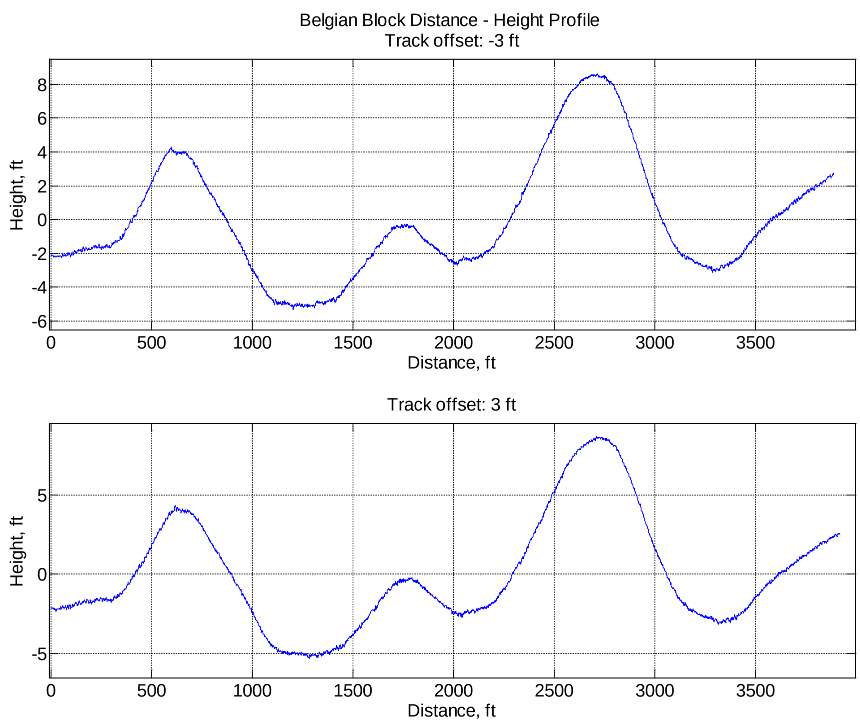

Figure A-5. Elevation plots of single line profiles.

APPENDIX A. ATC LASER PROFILER.

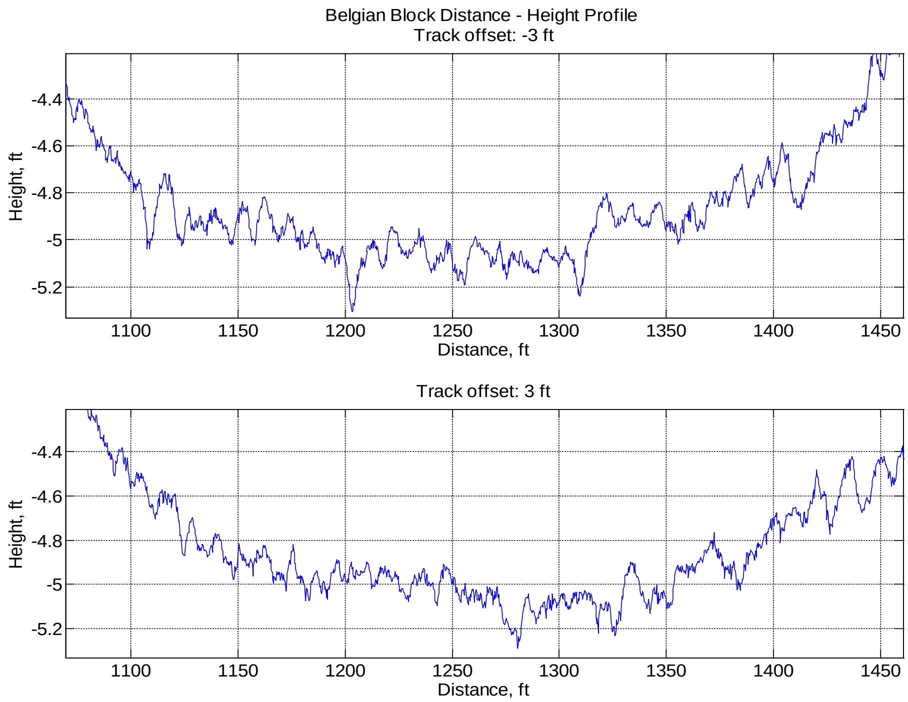

Figure A-6. Localized elevation plots of single line profiles.

A.3. <u>WHEELPATH TRACK PROFILES</u>.

a. Typically the reported profile metrics come from the HMMWV wheelpath tracks (± 3 ft). There are various reasons for this decision. One reason is to reduce processing time and data sets to manageable levels. Some courses have elevation profiles, and derived metrics, that are dependent on track position. The tracks from a HMMWV wheelbase provide a consistent reference that is pertinent to the profiler itself.

b. Perhaps the most important reason for taking profiles from the wheelpath tracks is to mitigate the fact that many ATC test courses can have deformable surfaces (mud, loose soil, and snow). The compressibility of these surfaces can vary. If the laser scanners were mounted on the front of the HMMWV, then the profile could be measuring the height of loose material which offered very little input to the vehicle tire. The purpose of profiling is to characterize the input to a vehicle suspension. Because of this it is best to measure the height of the ground after the vehicle tire has pressed away the deformable material, revealing the terrain content which is a significant input to the vehicle suspension. If the course content is not deformable then profiles derived from outside the wheelpaths should also be considered valid. An example of a deformable surface is provided in Figure A-7, which shows imprints in the ground from both a HMMWV and the ATC Cart Profiler (which has a wheel track width of 4 ft.)

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Figure A-7. An example of a deformable surface imprinted by wheelpaths.

A.4. LIMITATIONS.

a. The laser profiler has several limitations that should be considered when interpreting the data. Generally the data are intended to assess relative height changes for content which could influence a vehicle suspension, chassis, and powertrain. The errors in measured height changes over very long distances (or time) are governed by the differential GPS precision. The measurement errors over short distances (or time) are governed by the IMU precision. Generally the system is more precise than is needed for its intended use. A useful profile can be generated even when there are GPS signal losses by taking advantage of IMU precision and post processing with GPS signals from times preceding and following the signal loss. If an application requires greater fidelity, such as what could be needed for civil engineering, then more traditional land surveying techniques should be used.

APPENDIX A. ATC LASER PROFILER.

b. Other limitations are related to the laser scanner portion of the system. Because the system is rear-mounted, the laser scan can be obfuscated by back-spray and dust generated by the wheels. The system operator must drive in a manner so as to not exacerbate these problems and employ mitigating practices such as driving slower when necessary, using mud-flaps, possibly spraying the course with water prior to profiling or profiling early in the morning rather in the afternoons when the dust can be worse. Typically these problems are seasonal and can be avoided with experienced planning. Also, the laser system cannot measure beneath water, standing grass, or other vegetation such as fallen leaves. And obviously the system cannot measure content outside the scan width of 12 ft (approximately).

c. Lastly it should be recognized that the ATC Laser Profiler typically reports profiles and derived metrics from different track widths than the ATC Cart Profiler. Specifically the ATC Laser Profiler reports from ± 3 ft from the vehicle center to rely on the HMMWV track width, while the ATC Cart Profiler has a 4 ft track width and so reported from ± 2 ft from the center. This is not always relevant, and profiles from both systems should be considered valid. However there are some courses, such as Belgian Block, which show sensitivity to profile track selection.

A.5. SAFETY.

As a Class 3B laser system, the Laser Profiler could pose an eye hazard and is therefore subject to some safety restrictions. Refer to the test center Safety Office for site specific information. Typically this means that when operated over non-reflective surfaces there is a Nominal Ocular Hazard Area (NOHA) to the rear of the HMMWV extending to 6 ft on either side of the vehicle, as depicted by Figure A-8. Untrained personnel should avoid this area. Emergency Safety interlocks are located at several points on the HMMWV in case a person should enter the NOHA.

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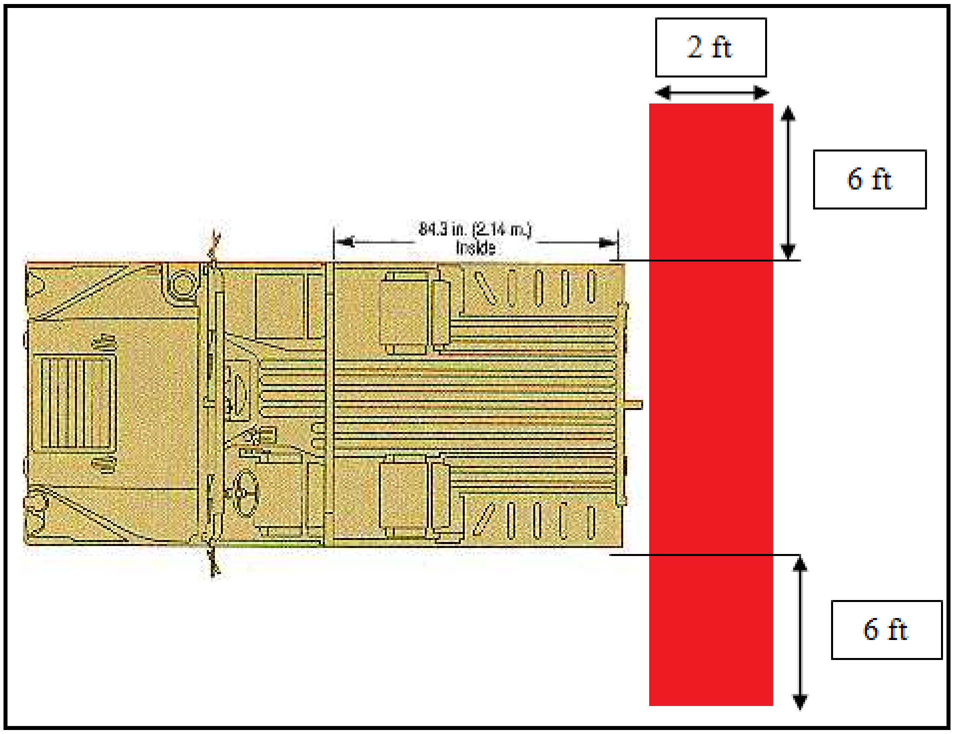

Figure A-8. Depiction of the NOHA (red).

APPENDIX B. YTC LASER PROFILOMETER.

Test course profiles are measured with the Terrain Severity Measurement System (TSMS) profilometer. The TSMS utilizes a 2006 Hummer H2 vehicle platform to make laser sensor-based terrain height measurements that determine a given course profile (Figure B-1). The TSMS is comprised of five spot laser sensors located on a platform in front of the vehicle, with one measuring in front of each of the left and right front tires and the remaining lasers evenly distributed along the width of the vehicle (the lasers are 17.3 in. apart and span a total width of 69.3 in.). While in operation, a GPS-based inertial navigation system is mounted on the platform containing the laser sensors to correct laser height measurements for vehicle attitude. In addition the cabin of the vehicle houses the data acquisition subsystem and mobile PC computer used to control data acquisition operations and monitor system performance.

Figure B-1. Terrain Severity Measurement System.

a. The TSMS contains a tactical grade GPS-based inertial navigation system to measure vehicle attitude (pitch, roll, and heading), geodetic position, velocity, and distance traveled at the measurement center of the IMU located on the laser platform. The inertial navigation system measurements are differentially post-processed using simultaneously recorded raw measurements from a separate GPS reference station located at a fixed known location near the area of operation (Figure B-2). Laser height measurements are corrected using the inertial navigation system to produce a local level reconstructed height profile at a rate of 200 Hz. In order to provide uniformly spaced distance measurements the 200 Hz data are decimated through an interpolation technique so that a distance sample interval of 0.25 ft is produced.

APPENDIX B. YTC LASER PROFILOMETER.

Figure B-2. GPS reference station.

b. The profile of a given terrain is calculated from the output measured by the inertial navigation system and the laser height measurements. As directly measured, the laser height measurements are in a vehicle body coordinate frame. The reconstructed profile rotates the measurements from the vehicle body frame to a local level north-east-up coordinate frame using a direction cosine matrix (DCM) that rotates in a ZXY order where Y is positive towards the front of the vehicle, X is positive to the right, and Z is positive up. The DCM is shown below. The reconstructed height profile adds elevation provided by the inertial navigation system to the local level laser height measurements.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\varphi\cos\psi - \sin\sigma\sin\psi\sin\varphi & \sin\psi\cos\varphi + \sin\varphi\sin\sigma\cos\psi & -\cos\sigma\sin\varphi \\ -\sin\psi\cos\sigma & \cos\psi\cos\sigma & \sin\sigma \\ \sin\varphi\cos\psi + \sin\sigma\cos\varphi\sin\psi & \sin\varphi\sin\psi - \cos\psi\sin\sigma\cos\varphi & \cos\sigma\cos\varphi \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

φ : roll
σ : pitch
ψ : heading
X : lateral direction in vehicle body coordinate frame
Y : longitudinal direction in vehicle body coordinate frame
Z : vertical direction in vehicle body coordinate frame
x : lateral direction in local level north-east-up coordinate frame
y : longitudinal direction in local level north-east-up coordinate frame
z : vertical direction in local level north-east-up coordinate frame

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

C.1. GENERAL.

a. An additional method ATC uses for characterizing roughness is to use an instrumented Test Course Inspection Vehicle (TCIV). The TCIV is an officially designated HMMWV that is used for no other purpose, to minimize wear and tear on the vehicle. The TCIV is used by an overview committee which periodically reviews the courses while operating the TCIV on the courses and reviewing profilometer output. The TCIV is outfitted with common instrumentation to enable an objective reference regarding the excitation of the TCIV by the test course. Each course has an objective speed which the driver attempts to maintain for the entire length of the course. Maintaining the same objective speed with the same vehicle and instrumentation enables the ability to make historical comparisons with the recorded data. For maintenance purposes, the data sets are compiled for approximately one-mile sections of the test courses.

b. Typically the TCIV is instrumented to measure road speed (sample rates greater than or equal to 1-Hz), right rear upper control arm acceleration (greater than or equal 50 Hz), and right rear upper control arm displacement (greater than or equal to 50 Hz). Additional instrumentation can be installed for more informational feedback. The data sets from each section are analyzed in post processing. Statistical metrics from the data sets are compared to limits set for each test course. The metrics which have historically been used are the difference between the 90- and 10-percent probability values for acceleration and displacement.

c. Test course inspections are typically conducted by the committee on a monthly basis. To obtain comparable data, the same committee inspects each course as in previous inspections using the same vehicle to minimize variables. Ideally the same driver is used for each inspection to minimize the influence of driving styles. The vehicle is maintained in the same condition as in previous inspections with particular attention given to the condition of its suspension system, shock absorbers, and tire inflation pressures.

C.2. EXAMPLE METRICS.

Example vehicle speeds and acceleration and displacement control limits for each ATC course are shown in Tables C-1 and C-2 and in Figures C-1 and C-2. These results are used in conjunction with the committee's assessment of course conditions and the results of the corresponding profilometer measurement to bring the surface roughness level to within its control limits.

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

TABLE C-1. ATC TEST COURSE INSPECTION SPEEDS

TEST COURSE	SPEED (mph)	SPEED (km/hr)
Munson Gravel	35	56
Belgian Block	25 (20 mph in turns)	40 (32 km/hr in turns)
Perryman A	35	56
Perryman 1	35	56
Perryman 2	25	40
Perryman 3	15	24
Churchville B – Smooth	35	56
Churchville B – Rough	20	32
Churchville C	30	48

TABLE C-2. ATC TEST COURSE INSPECTION LIMITS FROM INSTRUMENTED M1025 HMMWV

COURSE SECTION	ALLOWABLE RANGE
ATC Munson Test Area (MTA)	
Gravel Road, Section I:	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Section II	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Course Composite	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Belgian Block Course:	
Section I	
90- and 10-percent displacement, in.	1.2 to 1.7 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.3 *g*'s

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

TABLE C-1. CONTINUED

COURSE SECTION	ALLOWABLE RANGE
ATC Perryman Test Area (PTA)	
Perryman A Course:	
Section I	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Section II	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Course Composite	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Perryman No. 1 Course:	
Section I	
90- and 10-percent displacement, in.	0.5 to 1.2 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.4 *g*'s
Section II	
90- and 10-percent displacement, in.	0.5 to 1.2 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.4 *g*'s
Section III	
90- and 10-percent displacement, in.	0.5 to 1.2 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.4 *g*'s
Section IV	
90- and 10-percent displacement, in.	0.5 to 1.2 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.4 *g*'s
Course Composite	
90- and 10-percent displacement, in.	0.5 to 1.2 inches
90- and 10-percent acceleration, *g*'s	1.8 to 2.4 *g*'s

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

TABLE C-1. CONTINUED

COURSE SECTION	ALLOWABLE RANGE
Perryman No. 2 Course: Section I 90- and 10-percent displacement, in.	1.2 to 1.7 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Section II 90- and 10-percent displacement, in.	1.2 to 1.7 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Course Composite 90- and 10-percent displacement, in.	1.2 to 1.7 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Perryman No. 3 Course: Section I 90- and 10-percent displacement, in.	1.5 to 2.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Section II 90- and 10-percent displacement, in.	1.5 to 2.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Section III 90- and 10-percent displacement, in.	1.5 to 2.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Section IV 90- and 10-percent displacement, in.	1.5 to 2.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s
Course Composite 90- and 10-percent displacement, in.	1.5 to 2.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.5 *g*'s

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

TABLE C-1. CONTINUED

COURSE SECTION	ALLOWABLE RANGE
ATC Churchville Test Area (CTA)	
Churchville B Course (Smooth Section): Section I 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Section II 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Churchville B Course (Rough Section): Section III 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Section IV 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Section V 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Course Composite 90- and 10-percent displacement, in.	0.7 to 1.4 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s
Churchville C Course Course Composite	
90- and 10-percent displacement, in.	0.5 to 1.0 inches
90- and 10-percent acceleration, *g*'s	0.5 to 1.2 *g*'s

APPENDIX C. TEST COURSE INSPECTION VEHICLE.

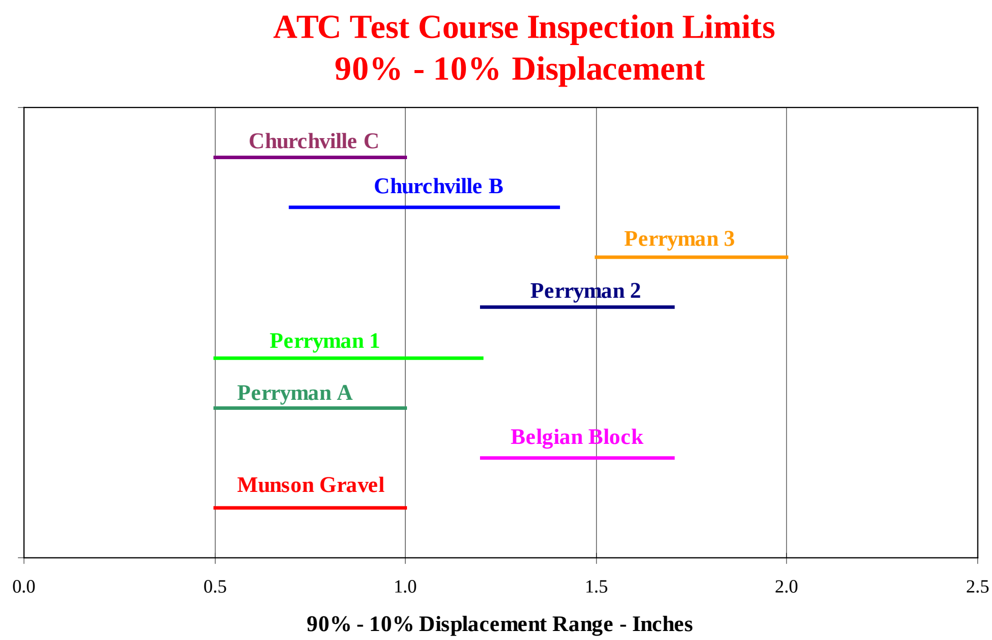

Figure C-1. ATC Test Course displacement range limits.

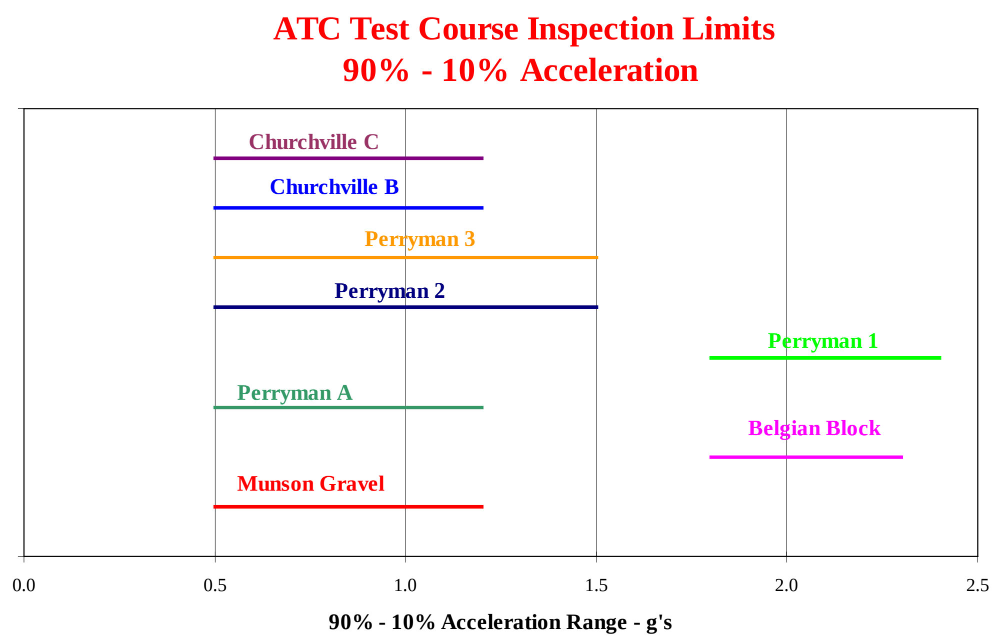

Figure C-2. ATC Test Course acceleration range limits.

APPENDIX D. ATC CART PROFILOMETER.

D.1. SYSTEM OVERVIEW.

a. Test course profiles are measured with a profilometer system. A system in frequent use from the early 1990's until 2011 was the ATC Profilometer Cart, which consists of a wagon type trailer (four wheels with two axles) drawn by a tow vehicle (Figure D-1), a data acquisition subsystem, and a mobile PE-computer-based data analysis system. The profilometer cart front axle is free to rotate about the yaw axis, but is constrained from other motion relative to the frame. A linkage to the drawbar is employed to constrain the front axle and align the wheels parallel to the drawbar. The rear axle is free to rotate about the roll axis and is constrained from all other motion relative to the frame. This system provides a platform which is articulate enough to conform to the anticipated terrain and to follow the tow vehicle. There are no compliant suspension components between the axles and the frame. Typically the cart is pulled at speeds less than 5 mph, both to limit vibrational input to the cart and to provide sufficient time for the acquisition control subsystem to maintain the same distance based sample rate.

Figure D-1. ATC profilometer cart and alternate prime mover.

b. The profilometer cart contains an inertial gyroscope to measure pitch and roll angle and two ultrasonic distance-measuring devices to measure the vertical distance between the frame and the terrain. In earlier implementations of the cart system the vertical gyro provided a signal to a stabilized platform so that the ultrasonic subsystem always pointed straight down. However this subsystem was eventually removed after it was deemed to add insufficient value for the increased complexity. A shaft encoder connected to the right rear wheel through a chain and gear system provides a pulse output as the system moves forward. A counter accumulates the pulses and an interrupt is issued to activate the data acquisition system at a programmable distance (currently 3 in.).

APPENDIX D. ATC CART PROFILOMETER.

c. The ultrasonic sensors are positioned within the left and right wheel paths of the cart, being located halfway between each axle. The ultrasonics are intentionally positioned within the cart wheel paths so that their measurements would be made on material that had previously been compressed by the front wheels. This was done to ensure easily deformable material did not add misleading content to the ground height measurement.

D.2. PROFILE CALCULATIONS.

a. The profile of a road surface is calculated from the pitch and roll angles and the ultrasonic subsystem outputs. The pitch angle data are first used to determine the locus of motion of the profilometer chassis' midpoint. A set of data are acquired at regular intervals of travel along the surface, from which the locus of travel at location *j* can be calculated from starting point 0 as:

$$y_{mp}(j) = \sum_{i=0}^{j} \sin(\theta_i) dl$$

$$x_{mp}(j) = \sum_{i=0}^{j} \cos(\theta_i) dl$$

where θ_i is the pitch angle at each of the measurements from the start of the measurement to location *j*, *dl* is the increment of travel along the surface (typically 3 in.) and x_{mp} and y_{mp} are the horizontal distance and elevation of the cart midpoints.

b. The left and right ultrasonic sensors at distance location *j* are at heights y_L^* and y_R^*:

$$y_L^*(j) = y_{mp}(j) + \frac{w}{2}\sin\phi_j$$

$$y_R^*(j) = y_{mp}(j) - \frac{w}{2}\sin\phi_j$$

where *w*/2 is the distance from the cart midpoint to each ultrasonic sensor and ϕ_j is the roll angle of the chassis.

c. Finally, the ultrasonic subsystem component is added to yield the elevation of the ground in the left and right tracks at location *j*, y_L and y_R:

$$y_L(j) = \sum_{i=0}^{j} \sin(\theta_i) dl + \frac{w}{2}\sin\phi_j + U_{Lj}$$

$$y_R(j) = \sum_{i=0}^{j} \sin(\theta_i) dl - \frac{w}{2}\sin\phi_j + U_{Rj}$$

where U_{Lj} and U_{Rj} are the j-th height distances measured by the left and right ultrasonic sensors, respectively.

APPENDIX D. ATC CART PROFILOMETER.

D.3. POST PROCESSING STEPS.

a. Because the pitch angle is constantly changing, the profiles obtained represent values obtained at a non-uniform sampling interval along the x-distance vector. Linear interpolation techniques are utilized to obtain samples at equal intervals of horizontal distance (typically 3 in.) as required by the spectral transformation. A digital filtering technique is also employed to account for the non-unity transfer function induced by the profilometer cart having a 6 ft wheel axle spacing.

b. After interpolation and wheel base correction filters are applied, high pass filtering is performed to remove long wavelength (low spatial frequency) data created by the integration process used in the above equations. Multiple sources of error influence the gyroscope's long wavelength content, but the integration process is most strongly influenced by offset errors. Historically a moving two-sided exponentially weighted average technique (detrending) algorithm was utilized, described in the U.S. Army Tank-Automotive Research and Development Center (TARDEC) (formerly known as TARADCOM) Signal Analysis Program[4], and shown mathematically as:

$$y_n(x) = \frac{\sum \{y(x + l\delta x) + y(x - l\delta x)\} e^{-l\delta x/\gamma}}{2\sum e^{-l\delta x/\gamma}} \qquad (sum\ from\ l = 0\ to\ E)$$

where:

$y(x)$ = elevation at point x.
$y_n(x)$ = correction factor.
l = step number.
δx = measurement interval (typically 0.25 ft).
γ = weighting constant.
E = limit of summation.

$$y_d = y - y_n$$

Where y_d(x) is the detrended elevation at point x.

D.4. LIMITATIONS.

a. Like all measurement systems, the profilometer cart system has some inherent flaws that influence the final profile. Some of the errors caused by these flaws can be mitigated through various post process filters. Others can be mitigated by recognizing the limitations and only using the cart profiles in certain ways.

APPENDIX D. ATC CART PROFILOMETER.

b. For example, the high pass filtering process described previously does not discriminate between low frequency data created as an artifact of the integration process (due to offsets in amplifiers and digitizers, etc.) and legitimate long wavelength data such as hills. Thus, the output of the cart profilometer is useful for describing surface roughness for wavelengths up to approximately 30 m (100 ft) (depending upon the detrending routine coefficients), and is inappropriate for measuring slopes. It is generally accepted among the terrain roughness community that wavelengths beyond 18 m (60 ft) have little effect on vehicle dynamics, and therefore can be ignored.

c. Another source of error is related to the cart having a 6-ft axle spacing. The cart wheel base essentially acts as a filter on the pitch channel of all wavelength content of 6 ft (and integer divisions of 6 ft.) Content at these wavelengths essentially raise and lower the front and rear axles in unison, meaning such content should cause no pitch excitation. Furthermore, because the ultrasonic sensors are located halfway between the axles, the ultrasonic channels will also be influenced by the cart axle spacing. Specifically the 6 ft and odd integer divisor wavelength content will be gained up by a factor of 2, while the even integer divisors of 6 ft will not be excited at all. Imperfections in cart geometry, wheel-ground interface, and axle spacing changes due to steering maneuvers mean that in practice the wheel base filtering will not be as extreme as this description implies. A digital filter was developed to provide some correction to the errors caused by the cart geometry, taking advantage of the attenuated content which was able to be measured despite the cart wheel base filtering. The filter routine is applied to the final distance elevation profile, as opposed the individual sensor channels. The digital filter’s improvements in signal fidelity was analyzed by using specific courses with known content that would be most influenced by the cart filtering, such as the Munson Test Area 6-Inch Washboard and 2-Inch Washboard courses.

d. Another source of error is related to the roll channel influencing both the right elevation signal and the left elevation signal equally without properly taking into account the true roll axis. For example, consider how a roll signal would be induced if the left side of the cart was on a smooth surface while the right side of the cart was being raised and lowered by obstacles. According to the equations above, the resultant profile of the left track would show content despite the fact that the left side of the cart traveled over a smooth surface. In practice, the roll center caused by most course content is approximately near the middle axis of the cart. Broadly speaking, most courses have an equal amount of random content in the left track as they have in the right track. The relevant point is that the profilometer cart will still convey a general sense of course content.

APPENDIX E. ABBREVIATIONS.

APG	U.S. Army Aberdeen Proving Ground
ASTM	American Society for Testing and Materials
ATC	U.S. Army Aberdeen Test Center
ATEC	U.S. Army Test and Evaluation Command
ATEF	Automotive Engineering Test Facility
AVEIRI	average international roughness index
CH	clay of high plasticity
CL	clay of low plasticity
cm	centimeter
CTA	Churchville Test Area
DCM	direction cosine matrix
DM	Desert March
FM	Field Manual
ft	foot/feet
ft/sec	feet per second
GC	clayey gravel
GCW	gross combination weight
GM	silty gravel
GP	poorly graded gravel
GPS	Global Positioning System
GVW	gross vehicle weight
GW	well graded gravel
HMMWV	High-Mobility multipurpose Wheeled Vehicle
Hz	Hertz
IMU	inertial mass unit
in.	inch
INS	inertial navigation system
IRI	international roughness index
KHSG	Kofa High-Speed Gravel
KLG	Kofa Level Gravel
km	kilometer
km/h	kilometers per hour

APPENDIX E. ABBREVIATIONS.

LHSG	Laguna High-Speed Paved
LHT	Laguna Hilly Trails
LHTSC	Laguna Hilly Trails Short Course
LLTE	Laguna Level Trails East
LLTW	Laguna Level Trails West
m	meter
ME	Middle East
MH	silt of high plasticity
MHz	Mega-Hertz
mi	mile
mm	millimeter
mph	miles per hour
MTA	Munson Test Area
NATO	North Atlantic Treaty Organization
NOHA	Nominal Ocular Hazard Area
OMS/MP	Operational Mode Summary/Mission Profile
PC	personal computer
PHG	Patton Hilly Gravel
PHT	Patton Hilly Trails
PLG	Patton Level Gravel
PLT	Patton Level Trails
PSD	power spectra density
psi	pounds per square inch
PTA	Perryman Test Area
RARS	Reference Average Rectified Slope
RL	Rock Ledge
RMS	root mean square
SM	silty sand
SP	poorly graded sand
SW	well graded sand
TARDEC	U.S. Army Tank-Automotive Research and Development Center
TCIV	Test Course Inspection Vehicle
TOP	Test Operations Procedure
TRTC	Tropic Regions Test Center
TSMS	Terrain Severity Measurement System

APPENDIX E. ABBREVIATIONS.

USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WNS	wave number spectrum
YTC	Yuma Test Center

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APPENDIX F. REFERENCES.

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APPENDIX G. APPROVAL AUTHORITY.

CSTE-TM 12 December 2017

MEMORANDUM FOR

Commanders, All Test Centers
Technical Directors, All Test Centers
Directors, U.S. Army Evaluation Center
Commander, U.S. Army Operational Test Command

SUBJECT: Test Operations Procedure (TOP) 01-1-010A Vehicle Test Course Severity (Surface Roughness), Approved for Publication

1. TOP 01-1-010A Vehicle Test Course Severity (Surface Roughness), has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency. The scope of the document is as follows:

This TOP describes methods for determining vehicle test course surface roughness and grades by analysis of profilometer data, as well as methods used for course maintenance. The calculated roughness metrics include normal displacement root mean square, wave number spectrum, international roughness index, and grade. This TOP includes the calculated metrics of vehicle endurance test courses at the Aberdeen Test Center, the Yuma Test Center, and the Tropic Regions Test Center.

2. This document is approved for publication and will be posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 2202 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Policy and Standardization Division (CSTE-TM), US Army Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activities: U.S. Army Yuma Proving Ground, Yuma Test Center, 301C Street, Yuma, Arizona 85365-9498, and U.S. Army Aberdeen Test Center, Automotive Directorate, 400 Colleran Road, Aberdeen Proving Ground, Maryland 21005-5059. Additional copies can be requested through the following website: http://www.atec.army.mil/publications/topsindex.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.